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The Effect of Moisture on Nonferrous Raw Separation

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Abstract

The goal of this project was to improve the liberation of nonferrous metals from nonferrous raw material at Schnitzer Steel Industries. The objectives were to understand the mechanics of cohesion between molecules and determine the effects of cohesion on screening and liberation efficiency. By conducting moisture analysis and sieve tests, an understanding of agglomeration and cohesiveness was developed. The moisture was determined to be the cause of clumping and has a direct effect on screening capabilities. The results conclude specific moisture contents have negative effects on screening capability at specific size ranges. Due to time constraints, further research must be conducted on a molecular level to verify that moisture is the cause of cohesion. In addition, the effects of moisture on industrial screening processes and liberation yield efficiencies should be studied.

1 Project Overview

This project was conducted to increase the liberation efficiency of nonferrous metals from nonferrous raw less than 10mm in size. To achieve this goal, we must determine the cause of cohesion in nonferrous raw material from Schnitzer Steel Industries. This first chapter is an overview of the project. First, a short background is provided to discuss the reasons for conducting this project. Second, the objectives of the project are presented including a discussion of the scope of the project. Lastly, an executive summary is included to overview the results, conclusions, and recommendations obtained from the project.

1.1 Background

Recycling plays an important role in the production of metals. While mining can produce metals by extraction and purification, the increase in demand for metals has caused the need for recycling to increase. In the United States in 2001, the recycling of end-of-use scrap metals accounted for the following percentages of domestic consumption: 12 percent of copper, 20 percent of aluminum, and 61 percent of lead (U.S. Geological Survey, 2001). While the main driving factors for recycling end-of-use metals seems to be stuck around the availability and market cost of scrap, recycling also plays an important role in environmental integrity. Mining and extraction of metals requires vast amounts of energy and CO_2 production, particularly for the production of copper (Norgate, Haque; Appendix A or Figure from article). The use of uncommon metals such as copper, titanium, stainless steel, and aluminums have increased with the advancements of technology. The environmental costs for producing these metals are significantly higher than the production of say, iron or bauxite (Norgate, Haque, 2009). Recycling is becoming increasingly important due to the increase in demand for metals, as well as the environmental benefits. However, metal recycling requires that recycling companies can compete with the market price of their main product, iron. When the market price of iron falls, the nonferrous metals that are recovered become more important. This is because metals such as stainless steel, aluminum, magnesium, and other nonferrous metals are a higher priced commodity. Therefore, these companies must find ways to recover the most nonferrous and precious metals possible.

Currently the main practice for the recycling of metals involves first shredding the material. Then the separation of this shredded material involves the treatment of the material first with rotating magnetic drums. If the material is too wet, the clumping of the raw material causes nonferrous metals to become entrapped during the ferrous separation process. This is the first problem with entrapment of nonferrous metals that occurs. After most of the ferrous material is removed, cyclone machinery and a hand picking station treat the leftover material (See Appendix A section 1.4 for detailed description). After these first steps, the leftover material is a mixture of rubber, glass, plastics, fibers, and nonferrous metals. This remaining mixture is called nonferrous raw (henceforth NFR). The NFR then undergoes further separation processes to liberate the nonferrous metals from the mixture. First, the material is screened to separate the NFR into specific size ranges. Once screened, special machines are used to extract the nonferrous metals from the mixture (See Appendix A for detailed description). It is on these special machines where cohesion amongst particles can affect the liberation efficiency, particularly for the smaller size ranges. When clumping occurs, these machines cannot liberate nonferrous metals from the NFR as effectively.

The principle goal of this project is to determine the cause of cohesion and entrapment amongst nonferrous raw material during the nonferrous liberation process. To achieve this goal, the first objective was to understand and determine the composition and moisture content of nonferrous raw material. Once an understanding of these material properties was obtained, experiments were performed to determine the effect of moisture on the separation of NFR by size range. Finally, once the mechanics of cohesion were understood, some initial observations were made. In addition, further research is pointed out that should be conducted to verify the results and help improve nonferrous liberation efficiency in the recycling industry.

1.2 Objectives

There are three objectives for this research program:

1. Understand the composition and moisture content of SNE nonferrous fines (< ⅜").
2. Understand the mechanics of cohesion.
    a) Understand the effects of cohesion on screening separation (specifically screening for industrial, and sieving for experiments).
    b) Understand the effects of moisture on cohesion.
3. Increase the efficiency of nonferrous liberation when the particle size is less than ⅜".

These four objectives illustrate the outline for this project. Research focused on material sized between 0 and ¾". While this size range is larger than the < 10mm (approx. ⅜") range outlined in the objectives above, it is important to understand the effect of cohesion on material larger than 10 mm. This is because during the extraction of nonferrous metals, the NFR is separated into size ranges starting with the separation of 0 to ¾". Then this cutoff is screened once more at ⅜". It is important to understand the effect of cohesion for 0 to ¾" because the distribution of material that ends up in the < ⅜" size range is affected by this cohesion. The scope of this research was limited to determining the impact of moisture content on separation. The sieve tests conducted show the effect of moisture on separation by size range.

However, this research must be corroborated using industrial screening techniques. In addition, other future research is discussed in the conclusions and recommendations section.

1.3 Summary

The current metal recycling process at Schnitzer Steel Industries involves the processing of NFR for the liberation of nonferrous metals less than 10 mm in size. Cohesion between molecules causes problems such as entrapment and overburdening. These problems significantly affect the yield of nonferrous metals and cause the yield of nonferrous metals to be less than the known amount of metals in NFR in this size range. The goal of this project is to determine the cause of these cohesive forces, determine the relationship between moisture and screening, and consider ways to increase the yield of nonferrous metals in this size range.

The initial observations of the project begin with the determination of the moisture content of NFR at Schnitzer Steel Industries, Northeast. The NFR less than 10 mm in size contains approximately 25% moisture content. The second observation is that the moisture content has a significant effect on the clumping of material. The third observation was that the interaction between moisture and the ferrous oxide "dust" which exists in the smallest size range of NFR could be a main contributor to the agglomeration and cohesion in the material.

The observations from this project point out the problems created by the existence of moisture in the material. While the results do not directly correlate the interaction between moisture content and nonferrous yield efficiency, they do provide insight into ways this efficiency can be improved. One such way is to reduce the overburdening of machinery by more effective screening processes (see results summary). A second way could be to reduce agglomeration by drying processes and therefore reduce entrapment and cohesion. Lastly, the following three points can be made regarding the use of both of these methods to achieve the goal of the project:

1. Moisture has an effect on the distribution of particles during screening of NFR.
2. By screening NFR at appropriate levels of moisture (specific to 3 a-d provided further testing), the different size ranges can be screened and separated more effectively.
3. These two points require further investigation on an industrial scale to determine the effect of their implementation on the yield of nonferrous metals during processing of NFR.

The observations and points made from this project are substantial, however, many of the proposed correlations and solutions (including the second point from above) must be substantiated through further testing and research. The corroboration of this data through the following recommendations will allow

Schnitzer Steel Industries to determine how to make an impact on the liberation efficiency of nonferrous metals. The first is to complete a detailed analysis of the cause of cohesion on a molecular level. The second is to observe the screening of material in industrial processes for NFR at different moisture contents. The third is to compare nonferrous yield while running NFR at different moisture contents. These recommendations are discussed in further detail in the conclusions and recommendations section of this paper.

2 Design of Experiment

This chapter includes the design of experiment. All pertinent information regarding the methodology, assumptions, and constraints is found in this chapter. To complete objectives 1 and 2 from above, experiments were conducted regarding the mechanics of cohesion amongst nonferrous raw (henceforth, NFR) particles. The first experiment was conducted to determine the moisture content of NFR. The second experiment was a series of sieve tests. Four different sieve tests were completed. The first two were completed using one methodology, but this methodology changed after some initial observations. The resulting sieve tests were completed to fulfill more specific objectives. Each of these three experiments: moisture testing, initial sieve tests and final sieve tests; are discussed in the following sections. The procedures in step by step form for these experiments can be found in Appendices B and C, respectively.

2.1 Moisture Content Tests

The first objective included determining the moisture content of Schnitzer Northeast's nonferrous raw material. Forty small samples (approximately 200 grams each) were dried using a furnace. The temperature used for drying was determined by the composition of material. The hottest allowable temperature would be around 110˚C due to some rubbers and plastics contained in the mixture. The drying time was determined by a control sample, which was allowed to dry for three hours with a weight recording every 30 minutes. After two hours, the weight did not change, so two hours was used as the drying time for all 40 samples. The weight of each sample was recorded for before and after drying. In addition to recording the weights, the time of day, temperature, humidity, and the pre and post-drying densities (in lb/ft^3) were also recorded. The densities were calculated by dividing the weight by the volume of the material for each sample. A 750 mL beaker with 25 mL increments was used to calculate the volume. This was done for both pre and post drying densities. The moisture content was also calculated for all 40 samples.

2.2 Initial Sieve Tests

The second objective was to understand the effects of cohesion on separation techniques. To begin, a sieve analysis was conducted to determine the effect of moisture on particle size distribution. A complex and precise procedure was determined and can be found in Appendix C. The following paragraphs contain a simplified overview of the steps taken during the tests.

Before the experiment could begin, a couple parameters were determined. The first was to determine the length of time a sample should dry and at what temperature. Because of the larger sample size than the moisture experiment, the drying time for a sample to reach 0 % moisture varied from sample to sample.

However, the drying process was still controlled with the following factors: where and how the samples were dried, the temperature at which the samples were dried, and also the length of time in the furnace. The samples were all dried in a convection furnace at 110° C. The drying time was determined by extending the length of time for a test sample in the furnace until all particles were light in color. The test sample was dry at around 13 hours. However, to make sure all the material would be dry for the control of the experiment, at a burden depth of 1.5 to 2 inches the drying time in the furnace was taken to be 15 hours. The second parameter determined was the sieve resonance time. The sieve resonance time was determined based on research of other sieve analysis tests and literature on sieve analysis. For the purposes of this experiment, the sieve resonance time was determined to be 10 minutes.

Next, the setup of the experiment involved acquiring the right materials so the sieve analysis could be completed with as little error as possible. This began with using a scale with .001 accuracy that could handle the weight of material used for the experiment. The scale was then placed within 5 feet of the sieves and sieve shaker on a separate table. Also on this table, new plastic sheeting was placed down for each sample to reduce the amount of material lost during the experiment. For this sieve analysis the following sieve sizes were chosen: ½”, 3/8”, #4 (.187”), #8 (.0929”), #16 (.04”), and a bottom pan. Each of these sieve’s weights was recorded before each sieve test to ensure weight measurement accuracy. A sieve shaker with a timer set to ten minutes was used to control the sieving process. The sieves were stacked in descending size from the largest sieve (1/2”) on top to the smallest (#16 then bottom pan) on bottom.

To begin the experiment, 5 gallon bucket samples of nonferrous raw were taken from Schnitzer Steel Industries. In total, four of these samples were taken: two from a 0 to ⅜” size range, and two from a 0 to ¾” size range. The ⅜” samples were taken from the vibrating feeder after the BiviTech ⅜” screen in the nonferrous processing plant. The ¾” samples were supplied by Ben Ghiringhelli. For the sieve analysis, each sample was taken one at a time to be dried, and then the procedure was carried out. Only after one sample had been completely finished did the process start over again. This was to ensure that the sample was completely dry at the beginning of the sieve testing.

For each sample, once dried, the first step was to split the sample into four similarly sized samples. Then, each of these four samples was put through the following procedure. First, the 0% moisture sample was weighed, and then poured into the top sieve. The sieve shaker was turned on with the timer set to ten minutes and after the ten minute period, the sieves were removed. Each sieve was weighed individually to determine the weight of material on each sieve. Then the sample was reconsolidated on the plastic sheeting on the table. The sieves were cleaned, recovering as much material stuck in the screens as possible. The sample was then shaken up and mixed together inside the plastic sheeting to redistribute the sizes of material throughout the mixture. From the original weight of the sample, the correct amount of water was calculated to equal 10% of the total weight. This amount of water was then added by spraying the material evenly with a fine mist squirt bottle. Once this moisture was added, the sample was poured into the sieves again, with the timer on the shaker set to 10 minutes. The sieve weights were recorded again and the same process of reconsolidating the sample was repeated. Then the correct weight of water was added to equal 20% of the total weight of the sample. The sieve test was repeated with the 20% moisture content material for another ten minutes and the weights recorded once more. This process was repeated for all four smaller samples of each of the 5 gallon samples. For each set of four smaller samples, the weights on each screen for each sieve test were totaled to consolidate the data into bigger sized samples. The reconsolidation of the samples during this process could possibly have interfered with the size distribution of material in the 10% and 20% moisture tests.

2.3 Final Sieve Tests

After the initial sieve tests, additional tests were done to validate the results. These tests utilized a slightly different procedure, which was proposed by Schnitzer employee, George Trezek. The procedure was the same except for the way each sample was handled. Rather than reconstituting a sample to test it at each moisture content, each sample was only used once, at one moisture content. This was done to verify that the reconstitution of the samples in the first sieve tests did not interfere with the particle size distribution of the samples.

In addition to verifying the results from the first sieve tests, these tests were also altered in two ways. The first was to introduce smaller increments of moisture content, which were decided to be 2%. Thus, the effect of moisture could be determined on a more specific scale of 0, 2, 4, 6, 8 10, etc. This was done to pinpoint more specifically the effect of moisture on separation between 0-10% and 10-20%. The second alteration was the sieve sizes used. For these second sieve tests, the sieve sizes were changed to more closely mimic the actual screening sizes used during Schnitzer processing. The sieve sizes used for the testing of <3/8” material were 1 mm, 2.4 mm, 4.75 mm, 6.3 mm, and 9.5 mm. For the testing of <3/4” material these sieves sizes plus the following were used: 12.7 & 15.9 mm.

For the testing of the 0-3/8” material, two 5 gallon samples were used. These two samples were split into 11 equal parts. Each of these 11 samples corresponded to 0%, 2%, 4%, 6%, through 20% moisture contents. This way each sample was only used once without having to be reconstituted. This was done to ensure the validity of the particle size distribution for each sample.

3 Results

The following sections contain an overview of the results compiled from the three experiments conducted for this project. The first experiment shows results for the moisture content of NFR. The second experiment was the initial sieve analysis tests, which were completed using the reconstituted method described in section 3.2. The third and final experiments were the resultant sieve analysis tests completed by following the method described in section 3.3.

3.1 Moisture Content Results

The moisture content of 40 small samples of 3/8" and smaller nonferrous raw was recorded during the moisture analysis tests. The average moisture content of these 40 samples is 25.84%. The moisture content of each of the forty samples compared to the average moisture content can be seen below in Figure 1. Because of the small sample sizes, the distribution widely varies, with 6 of the samples lying outside of the standard deviation. However, the average moisture content is still a valid number because verification of this number came through the drying out of two 5 gallon samples (0-⅜" NFR) during the sieve analysis experiment. These two 5 gallon buckets together weighed four times the amount of all 40 samples combined. The first 5 gallon sample initially weighed 33.171 lbs., and after drying weighed 24.636 lbs. The moisture content of this sample was 25.73%. The second 5 gallon sample initially weighed 37.985 lbs., and after drying weighed 28.429 lbs. The moisture content of this sample was 25.16%. From the data gathered during the experiments with 0-3/8" NFR, the moisture content can be placed somewhere between 20 and 30%, with the most likely average being around 25%.

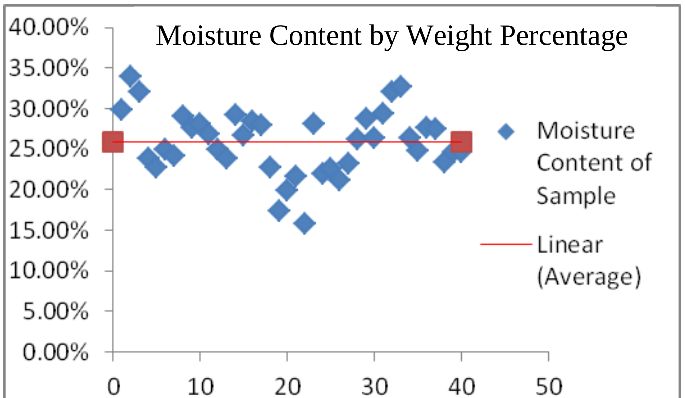

Figure 1 - Sample Moisture Percentages with Mean

In addition to moisture content, additional data was gathered during the moisture content tests on density, humidity, temperature, and other points. This data can be found in Appendix B after the procedures.

3.2 Initial Sieve Test Results

The results from the initial sieve tests can be split up by sample size. Two samples of 3/8" NFR and two samples of ¾" NFR were used for the sieve tests. The results reflect the size distribution of each sample at 0%, 10%, and 20% moisture content. The dramatic effects of moisture on the size distribution show that the effects of moisture on the properties of nonferrous raw cannot be ignored.

3.2.1 Types of Material in Each Size Range

After sieving each sample at 0% moisture content, observations were made regarding the types of materials in each size range. With the material at 0% moisture content, it is assumed that this shows the true distribution of materials in nonferrous raw based on size range. The top two size ranges are rich in nonferrous metals and are put through nonferrous processing at all Schnitzer plants. However, the material smaller than ¼" is sent to waste at some plants. Jason Coope stated it is estimated that 9% of the material less than ¼" in size is recoverable nonferrous metals. From the dried material in this experiment, this estimate is highly likely. In the size range of 4.75 mm to 9.53 mm many nonferrous metals are mixed with aggregate as can be seen in Figure 2 on the left. In addition, even one size range lower at 2.46 mm to 4.75 mm there is still nonferrous metals present. This can be seen in Figure 3 below as well. While there are more composite materials in this size range such as wood chips and glass particles, the shiny metals can clearly be seen in the picture. Also in this smaller size range is a significant amount of copper wiring. In the two lowest size ranges, the mixture is nearly all ferrous oxide "dust" and wood splintering.

Figure 3 - Picture of 4.75 to 9.53 Size Range at 0% Moisture Content

Figure 2 - Picture of 2.46 to 4.75 Size Range at 0% Moisture Content

George Trezek verified the visual observations about the content of metals in each size fraction with his own studies. His numbers may slightly vary from the NFR at Schnitzer Northeast, but they still represent a general percentage of the size range that is metal. These numbers are presented in correspondence with the discussion in the conclusions and recommendations section.

3.2.2 ⅜" Sample Size Distributions

The first results obtained were the simple size distribution graphs. In these graphs the percent of the total weight on each sieve is graphed against the size range. As seen in Figure 4 on the next page, these graphs are a good way to simply show what percentage of the material in each sample was in each size range. For sample 1 at 0% moisture content, 45% of the material fell into the smallest size range. The material at this size range is referred to as "dust", and has been cited by Jason Coope as being predominantly ferrous oxide. Throughout the experiment, it became apparent that this ferrous oxide is one of the main causes of clumping on the screens with the addition of moisture.

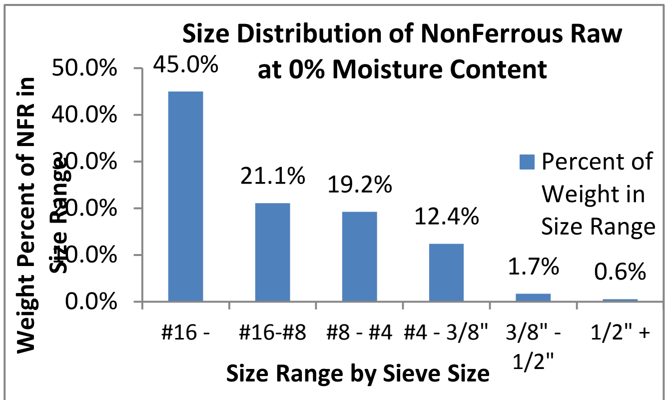

Figure 5 - Size Distribution of Sample 1 at 0% Moisture

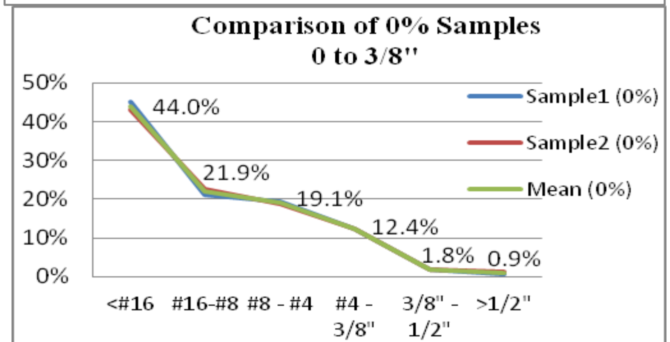

Figure 4 - Comparison of Size Distributions of Samples 1 & 2 at 0% Moisture

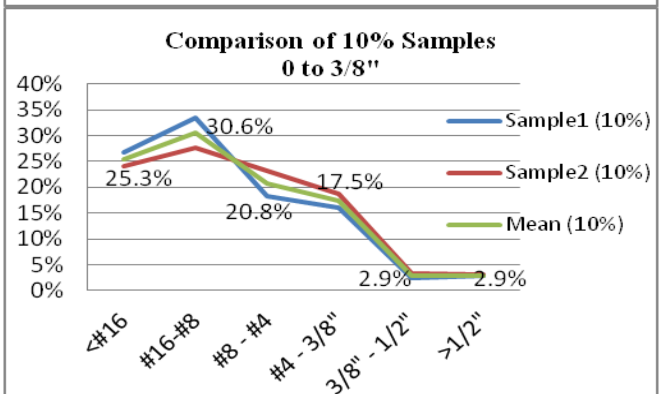

Figure 6 - Comparison of Size Distributions of Samples 1 & 2 at 10% Moisture

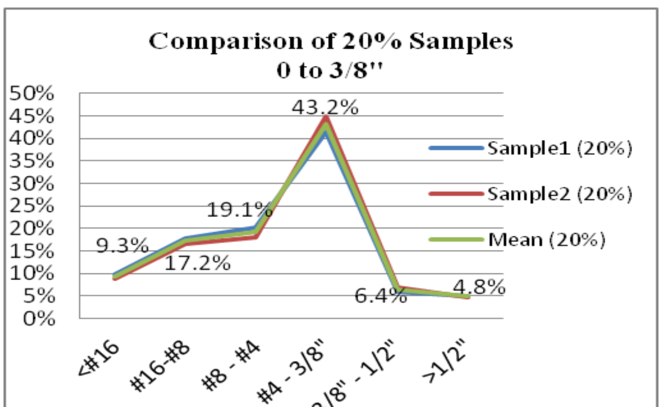

Figure 7 - Comparison of Size Distributions of Samples 1 & 2 at 20% Moisture

The two ⅜" samples produced similar size distribution results for the 0, 10, and 20% moisture content tests. The following graphs compare the two samples and their mean. To save space, the axis titles are omitted. The y axis is the weight percent of NFR in each size range, and the x axis is the size range by sieve size. Figure 4 is the distribution at 0% moisture. Similar to above, around 44% of the total weight of material is found in the smallest size range (<1mm). Also, note that the mean follows the distribution of the two samples closely, and that the difference between the percentages of the two samples is less than 2% for all size ranges.

Although the variation from sample to sample for 0% moisture was quite small, this is not the case for all percent moisture contents. However, the mean will be taken as a valid estimate for the purposes of these initial sieve experiments.

Figures 6 and 7 show the comparison of size distributions of samples 1 and 2 for 10% and 20% moisture contents. The distributions vary greatly once moisture is added to the samples. The most notable effects from 0% to 20% moisture contents are the large decrease in material from the smallest size range, and the large increase in material on the #4-3/8" (4.75mm-9.53mm) size range.

An important point to observe from this data is what percentage of moisture creates the largest effect. From 0% to 10% moisture content, the largest loss of material occurs in the lowest size range. However, largest increase in material

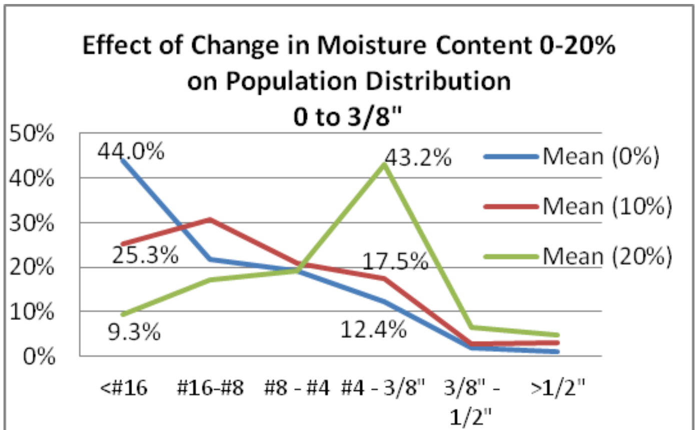

Figure 8 - Comparison of Mean Size Distributions at 0, 10, and 20% Moisture Contents

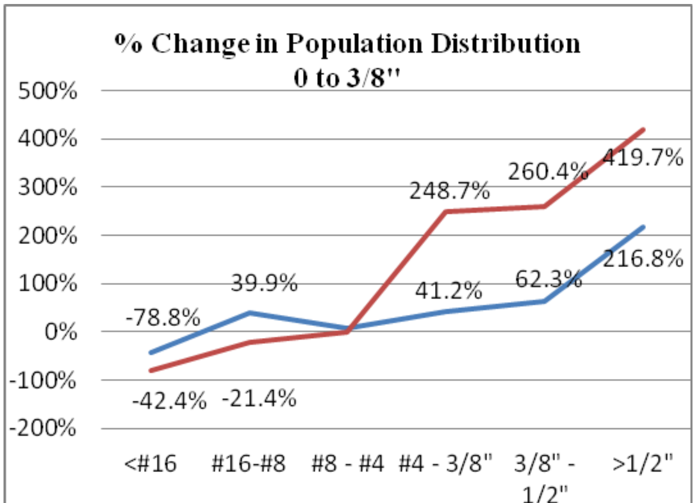

Figure 9 - Graph Comparing the Percent Change of Material in Each Size Range from 0-10% and 0-20%

occurs from 10% to 20% on the #4 screen. The effect of change in moisture content is shown more clearly in Figure 8 on the left. This graph compares the mean distribution of samples 1 and 2 for 0%, 10%, and 20% moisture contents. The graph clearly shows where the largest changes in the weight percent of material occur. In addition to Figure 8, Figure 9 includes more data regarding the percent increase or decrease of percent weight of material. From 0-10%, the largest percent increase occurs from clumping on the top two screens, but the amount of material on these two screens is minimal. The more significant datum is that the largest decrease occurs on the smallest screen size. This means most ferrous oxide is transferred from the bottom pan to clumping in other areas during the transition from 0-10%. However, it is just as important to consider that there is significant increases in material weight on the three larger screens from the transition of 10-20% moisture.

3.2.3 ¾” Sample Size Distributions

Similar to the 0-3/8” sample, these distributions were also graphed using line graphs to compare each sample. The graph in figure 10 on the following page is the comparison of the two samples and their mean at 0%. The two samples once again follow their mean reasonbly closely. This is important to determine the validity of the samples. In the 10% and 20% moisture content sieve tests the mean was matched even more closely than in the 0% test. These two comparison graphs were placed in Appendix C. Because the sample size was larger than for the 0-3/8” samples the distribution was shifted to the right on these graphs. This means that less material was in the smaller size ranges and more material was in the larger size ranges.

These graphs show that the distribution is affected mostly in the middle size ranges when moisture is added. The amount of material on the screens with size ranges above #4 are only slightly increased. In Figure 11 this is illustrated by graphing the 0%, 10%, and 20% mean distributions. The green line representing 20% moisture content in Figure 11 shows that material less than the #4 screen (4.75 mm) is being entrapped on screens larger than the #4 screen (4.75mm holes). This is illustrated by the green line dropping below the blue and red lines on the left side of the graph, and rising above the red and blue lines on the right side of the graph. As the line decreases, this means more material is becoming entrapped on the larger screens. However, it is interesting to note that the percent change of material in each screen size shows remarkably different results. Figure 12 below shows the percent change between 0-10% and 0-20% moisture contents. This graph shows that while the percent of weight on each screen does not appear to change much, the difference in weight change is actually greater for the screen sizes larger than the #4 screen. This means that there is a large change in the amount of material on the larger screens from 0%-20% moisture content. This is important to point out because this means that while the effect on the large size ranges was seemingly minimal in Figure 11, the actual change from 0%-20% was

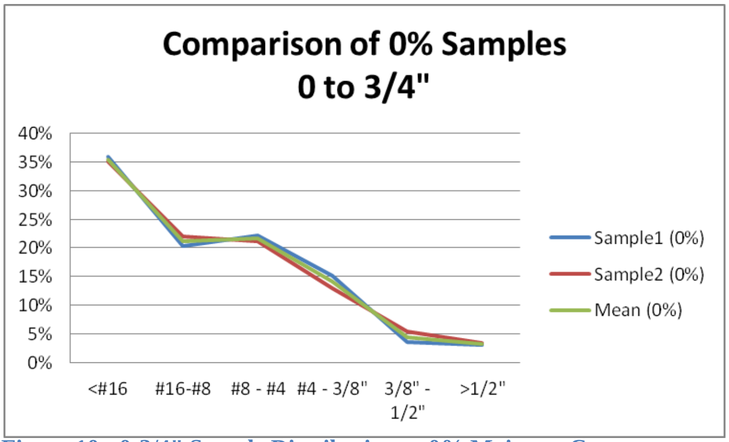

Figure 10 - 0-3/4" Sample Distribution at 0% Moisture Content

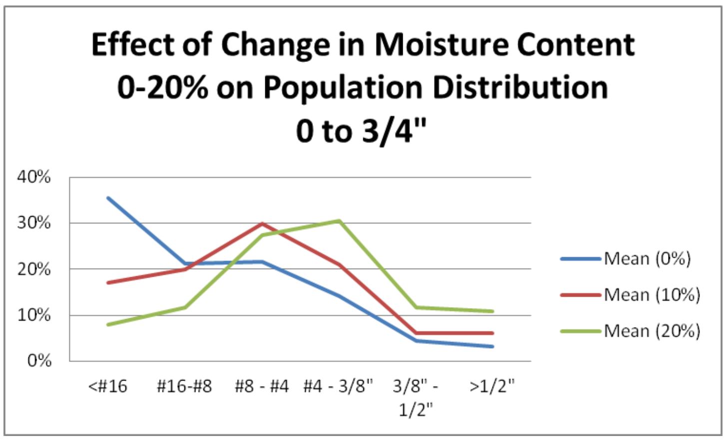

Figure 12 - Comparison of Distributions for 0%, 10%, and 20% Moisture Contents

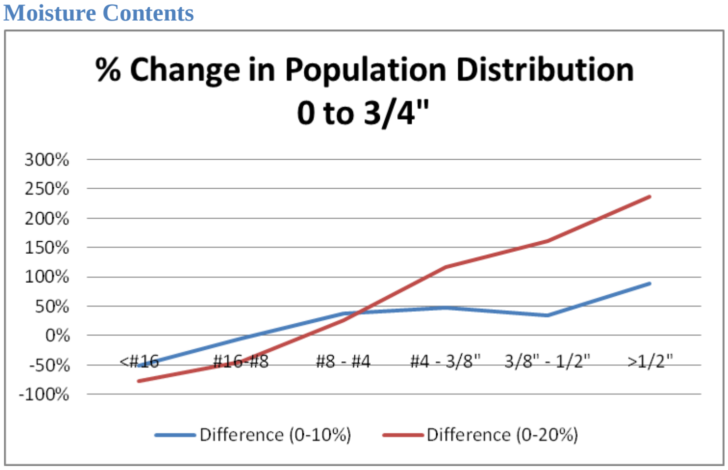

Figure 11 - Percent Change Between Moisture Contents 0-10% and 0-20%

around 250%. This is a significant change in the amount of material added to these size ranges and warranted a need for further investigation.

3.3 Secondary Sieve Tests

The following sieve tests were completed using the procedure outlines in section 3.3. These tests were conducted using 2% moisture increments to determine more precisely, how the addition of moisture affects the screening between 0%-10% and 10%-20% moisture contents. In addition, these tests used sieve sizes, which more closely corresponded to the actual sizes used during Schnitzer processing. This was done to more closely determine the effect of moisture on size ranges used in industry.

3.3.1 ⅜" Sieve Tests at 2% Moisture Increments

For the ⅜" sample, the sieve sizes had openings of 1 mm, 2.4 mm, 4.75 mm, 6.3 mm, and 9.5 mm. These sieve sizes slightly altered the overall particle size distribution compared to the previous sieve tests. As shown in Figure 13 to the left, the distributions for the new sieve sizes are more evenly distributed between the 4.75-9.5 mm ranges. This is because the extra screen at 6.3 mm holds some particles rather than the large amount of material that was previously seen on the 4.75 mm screen. This provides a true distribution because the sample is distributed over a more evenly spread size ranges than from the initial sieve tests.

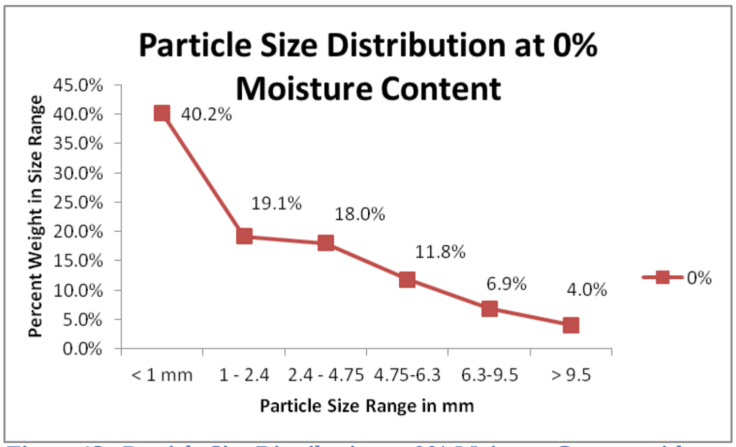

Figure 13 –Particle Size Distribution at 0% Moisture Content with New Sieve Sizes

The particle distributions are shown at 2% moisture increments in Figure 14 on the left. This figure shows the distributions for 0-10% moisture contents. The graph shows that for material larger than 6.3 mm there is little to no change in distribution from 0-10% moisture contents. The graph also illustrates that in the 4.75-6.3 mm size range the clumping begins to occur between 6-8% moisture contents. Material less than 4.75 mm is greatly affected by moisture contents

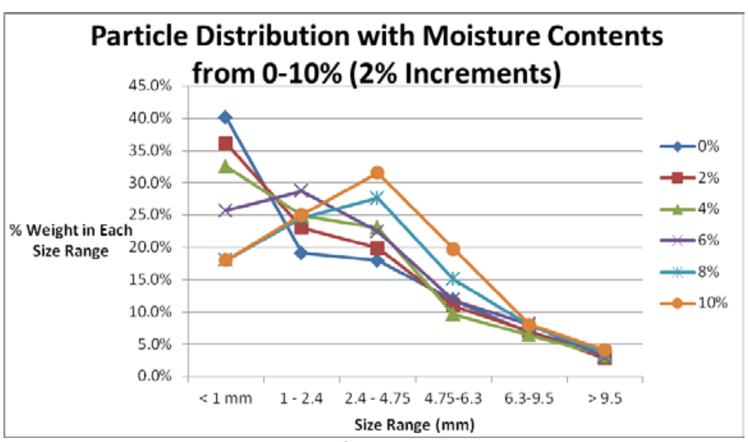

Figure 14 - Particle Distribution from 0-10% Moisture Contents at 2% Increments

from 4-6% and higher as shown by the increased amount of material in the 2.4-4.75 mm size range due to clumping.

The graph in Figure 15 below shows the particle distribution for 10-20% moisture contents at 2% increments. The orange line represents the distribution at 10% moisture content, which was the same color in Figure 14. While the moisture content below 10% does not have much effect on particles larger than 6.3 mm, when the moisture content rises above 10% there is a rise in the amount of material in the 6.3-9.5 mm size range. This graph shows that the amount of material less than 6.3 mm in size is decreasing as the moisture content goes from 10-20%. As the smaller particles become more saturated with moisture (above 10%), the amount of material in the larger size ranges increases, particularly in the 6.3-9.5 mm size range. The amount of material above 9.5 mm in size increases, but not as significantly as in the 6.3-9.5 mm size range. This is because 9.5mm is the upper limit for size in a ⅜" sample.

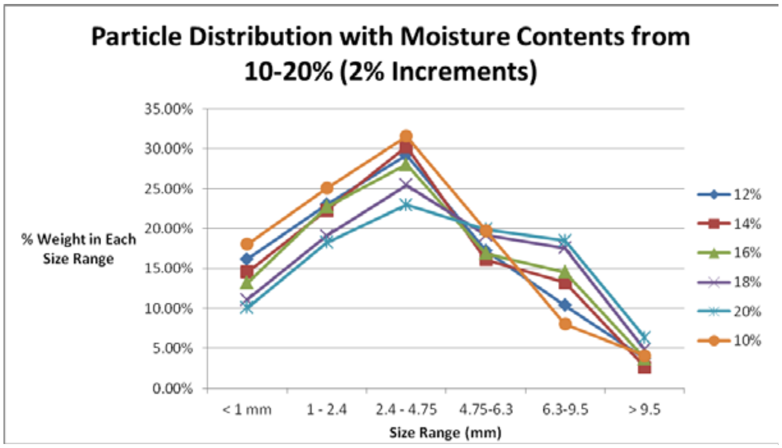

Figure 15 - Particle Size Distribution from 10-20% Moisture Content at 2% Increments

The following graph in Figure 16 shows the particle distributions at 0%, 10%, and 20% moisture content for these tests. Clearly depicted is the effect of moisture on the 4.75-6.3 mm size range from 0-10% moisture contents, while from 10-20%, there is little effect. For the 6.3-9.5 mm size range, during the 0-10% increase in moisture content, there is a minimal effect from moisture. However, from 10-20% moisture content there is a large effect of increasing moisture content on the 6.3-9.5 mm size range.

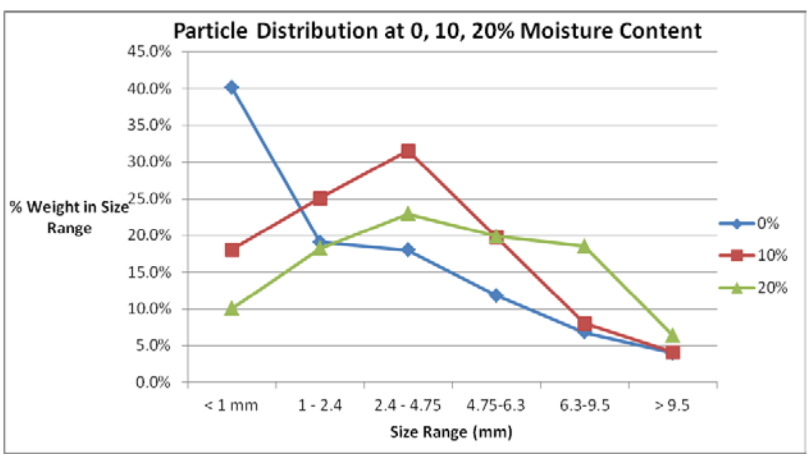

Figure 16 - Particle Distribution for 0, 10, & 20% Moisture Contents

More specifically, these effects are shown quantitatively in Figure 17 on the next page. For these calculations, the percent change between moisture contents is considered. This represents the change between the percentage of material in the each size range at 0% compared to the percentage of material in that size range at 10%. For example, from 0% to 10% moisture content, there was a 55% reduction in the weight percentage of material in the <1 mm size range. In the same size range, from 0% to 20% moisture content there was a 74.95% reduction in the weight percentage of material. This means that for the <1 mm size range, the most material is lost from 0-10% (50 weight %), then an additional 25 weight percent are lost from 10%-20% moisture contents. The most important results to take away from this study are at what moisture contents the specific size ranges are most affected. As moisture content increases, the ferrous oxide from the smallest size range clumps up with other particles, causing the distribution between size ranges to change. From 0% to 10% moisture content, there is a 66.93% increase in the weight percent of material in the 4.75-6.3 mm size range. Then, from 10-20% moisture content, the weight percent of material in this size range remains the same. This means that from 0-10% moisture content, the amount of clumping that occurs on the 4.75 mm screen reaches a near maximum. There is little difference in weight percent of material left on the screen when the moisture content is increased to contents above 10%. This is significant because this means that the material being lost from the smaller size ranges is then clumping elsewhere at moisture contents above 10%. For size ranges smaller than 4.75 mm, there is a decrease in the weight percent of material when the moisture content rises above 10%. The weight percentage that is lost from the smaller size ranges is shifted to the sizes 6.3 mm and up. This is seen by the 170.12% increase in weight percent of material in the 6.3-9.5 mm size range from 0-20% moisture content. In addition, there is a 57.94% increase for the >9.5 mm size range. It is important to note that there is significantly more change in these two size ranges once the moisture content rises above 10%.

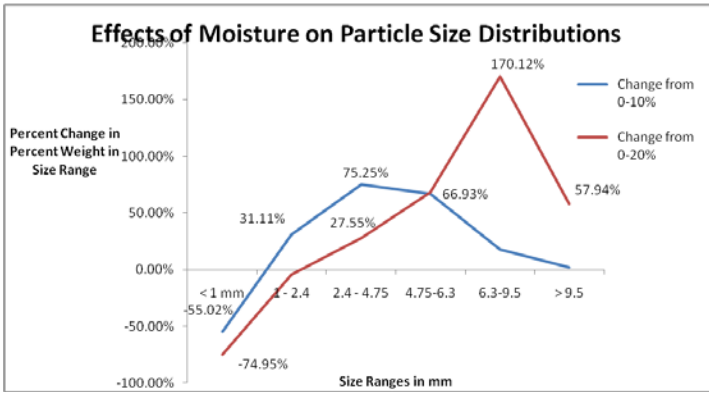

Figure 17 - The Percent change in weight percent of material in each size range based on moisture content

This can be examined more closely by focusing on the changes that occur between 10% and 20% moisture contents for the three largest size ranges. From the data in Figure 18 on the left we can focus on when moisture begins to affect the percent of material in these size ranges. Each line represents the percent change from 10% to the percentage listed. Of particular interest is where the >9.5 mm size range begins to agglomerate material. The first increase in the weight percent of material in this size range

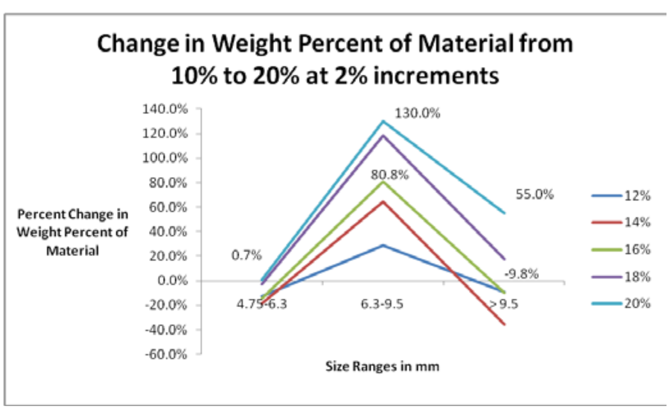

Figure 18 - Effect of moisture on weight percent of material at 2% increments for three largest size ranges

occurs from 16% to 18%. In the size range of 6.3-9.5 mm, there is increase seen in every increment after 10%. For the 4.75-6.3 mm size range, there is little change when the moisture content is greater than 10%. While the larger size ranges are effected more at moisture contents above 10%, the smaller size ranges need to be analyzed between the moisture contents between 0% and 10%. This is because this smaller material is much more sensitive to moisture. For this reason, a similar graph to Figure 18 above (shown left in Figure 19) was created to compare the effects of moisture between 0-10% contents at 2% increments. The four smallest size ranges were included. The two size ranges of focus are the two larger ones because fewer metals can be found in the two smallest size ranges. For the 4.75-6.3 mm size range, the effect of moisture begins to increase the weight percent of material once the moisture content reaches 6%-8%. At 6%, there is no percent change from 0%, but there is an increase in weight percent from 4% moisture. At 8%, the change in weight percent from dry material is a 27.5% increase. For the 2.4-4.75 mm size range, moisture increases the amount of agglomeration when it is greater than 0%. These results and their importance will be discussed in greater detail in the conclusions and recommendations section of the paper.

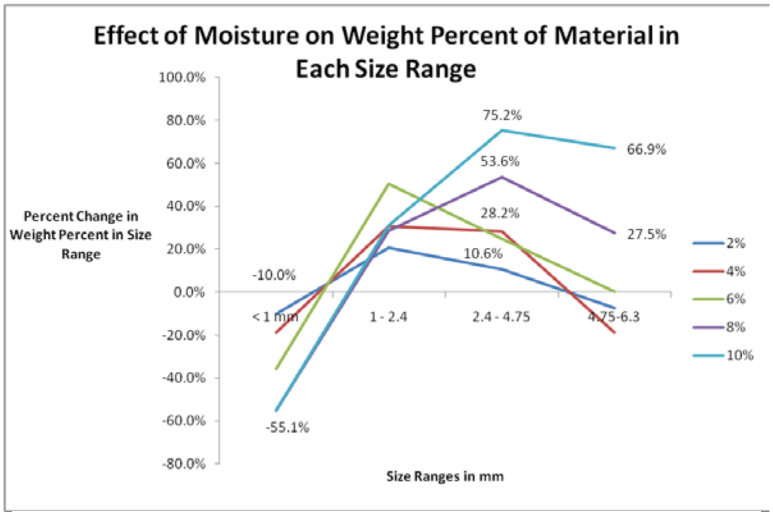

Figure 19 - Effect of moisture on weight percent of material at 2% increments for the four smallest size ranges

3.3.2 ¾” Sieve Tests at 2% Moisture Increments

For the ¾” sample, the sieve sizes had openings of 1 mm, 2.4 mm, 4.75 mm, 6.3 mm, 9.5 mm, 13.0 mm, and 16.0 mm. These sieve sizes slightly altered the overall particle size distribution compared to the previous sieve tests. The testing of the ¾” sample was completed to better understand the effect of separation on NFR slightly larger than 10mm. This allows us to verify the results from the ⅜” sample and determine the effect of moisture on particles larger than 10 mm. This is important because in industry NFR is often screened at ¾”.

The particle distributions are shown at 2% moisture increments in Figure 20 on the following page. This figure shows the distributions for 0-10% moisture contents. The graph verifies that for material larger than 6.3 mm there is little to no change in distribution from 0-10% moisture contents. The graph also verifies that in the 4.75-6.3 mm size range the clumping begins to occur between 6-8% moisture contents. In the 2.4-4.75 mm size range moisture content above 4% causes clumping.

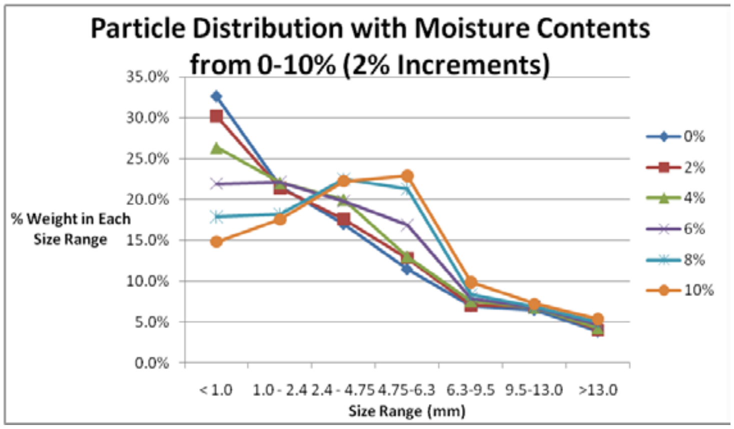

Figure 21 - Particle Distribution from 0-10% Moisture Contents at 2% Increments

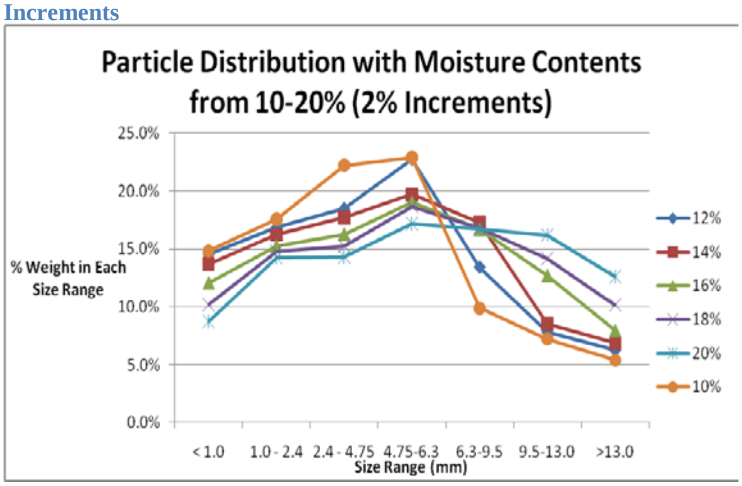

Figure 20 - Particle Size Distribution from 10-20% Moisture Content at 2% Increments

The graph in Figure 21 below left shows the particle distribution for 10-20% moisture contents at 2% increments. The orange line represents the distribution at 10% moisture content, which was the same color in Figure 20. While the moisture content below 10% does not have much effect on particles larger than 6.3 mm, when the moisture content rises above 10% there is a rise in the amount of material in the 6.3-9.5 mm size range. This reaches a maximum amount around 14% moisture content. This is because clumping begins to occur rapidly from 14% to 16% moisture content for the 9.5-13.0 mm size range. For NFR larger than 13.0 mm, moisture begins to really effect screening from 16%-18% moisture content. This graph corroborates the ⅜" sieve tests because it shows that the amount of material less than 6.3 mm in size is decreasing as the moisture content goes from 10-20%. As the smaller particles become more saturated with moisture (above 10%), the amount of material in the larger size ranges increases. These results and their importance will be discussed in greater detail in the conclusions and recommendations section of the paper.

3.4 Summary of Results

The results obtained from these experiments can be summarized with the following four points:

1. The nonferrous raw samples taken from Schnitzer Northeast in the size range 0-⅜" contains approximately 25% moisture by weight percentage.
2. The moisture in this material causes agglomeration to occur on the sieves during screening.
3. The moisture content begins to increase the weight percent of material in each size range at specific amounts of moisture:

a. NFR from 2.4-4.75 mm begins to agglomerate when moisture content reaches about 4-6%.
b. NFR from 4.75-6.3 mm begins to agglomerate when the moisture content reaches 6-8%.
c. NFR from 6.3-9.5 mm begins to agglomerate when the moisture content reaches 10-14%.
d. NFR from 9.5-13.0 mm begins to agglomerate when the moisture content reaches 14-16%.
e. NFR greater than 13.0 mm begins to agglomerate when the moisture content exceeds 16-18%.

4. NFR can be more effectively screened (increase the number of particles less than the screen size that pass through) if dried to the correct percentage moisture content.

4 Conclusions and Recommendations

The results outlined in the previous section yield interesting points, which lead to much discussion. The sections below discuss the conclusions, which arise from this research and point the way towards future research. Included are a discussion of the mechanics of cohesion in NFR and a discussion of how the data from these experiments can correspond to the goal of this research paper: to increase the yield of nonferrous metals during liberation.

4.1 Mechanics of Cohesion

The change in weight of material in each size range is seemingly due to clumping that occurs on the screens when the material in the smallest size range absorbs moisture. This accounts for the loss of material in the smallest size range and also the increase in material on the 4.75 mm and 6.3 mm screens.

Figure 22 -4.75 mm Screen at 0% Moisture Content

Figure 23 – 4.75 mm Screen at 10% Moisture Content

Figure 24 -4.75 mm Screen at 20% Moisture Content

The evidence of this clumping can be seen clearly through the pictures on the left (Figures 22-24). Between 0 and 10% moisture content, there is quite an effect on the 4.75 mm (#4) screen. Then from 10 to 20% moisture, there is a huge amount of clumping as can be seen by the large amount of dark color. The screen is also no longer visible because it is completely obstructed by the clumping. Moisture has a similar effect for the 6.3 mm screen from the final sieve tests.

From the results, large amounts of ferrous oxide (< 1mm particles) was lost between 0-20% moisture. With this large decrease in the weight of less than 1 mm particles, there is an increase in the amount of material in the other size ranges. This means that most likely, these small particles, when absorbing moisture, tend to attach themselves to other particles and cause clumping. The results from the sieve experiments show that as moisture content increases, these small particles agglomerate into larger and larger particles with more moisture. From 0-10% moisture contents, there is an increasing number of particles in the 2.4-4.75 mm and 4.75-6.3 mm size ranges. However, as the moisture content rises further from 10-20%, the amount of NFR in the 0-4.75mm size ranges decreases as the clumping begins to trap more material in the 6.3-9.5 mm size range. Because of the suspicions about this ferrous oxide being the cause of cohesion amongst particles, some additional side experiments were conducted to explore the way this smallest size range interacts with moisture. A single sample was separated at 0% moisture content and the <1 mm ferrous oxide was placed in a pan.

Figure 26 - Picture of Ferrous Oxide with Moisture

The pictures in Figures 25 and 26 depict this interaction. To the left in Figure 25, a pan of ferrous oxide can be seen rejecting the water which is puddling up on top of the material. One reason this could happen would be due to the strong polarizability of ferrous oxide. The "dust" clings together with strong magnetic attraction due to the way the electrons are arranged around the molecules. In addition to this attraction force, the water molecules pool together due to the polar properties of water molecules. As seen in Figure 26, once the water has mixed with the ferrous oxide, the mixture becomes uniform and mud-like. Because of the high polarizability of both the ferrous oxide and water molecules, the mixture contains a relatively strong attractive force between molecules. London Dispersion Forces are a type of Van DerWaal's force which occurs between easily polarizible molecules. When mixed together, the electrons line up so that the positive and negative ends of the molecules are closest. A simple picture of this can be seen to the left in Figure 27. This picture was created in paint, based off of a drawing from a Stanford investigation into Van der Waal's forces. By looking into a more exact composition of the ferrous oxide "dust" that is present in NFR, a more comprehensive hypothesis could be made by considering the actual forces that are occurring on the molecular level. By determining the forces on the molecular level, other methods of drying could be considered, such as dispersants. Dispersants rely on the right amount being introduced to generate the anti-clumping effect. This amount is based on the chemical composition and amount of agglomeration forces. Further investigation into the mechanics of cohesion is warranted to determine more specifically the forces at play on a molecular level. A complete understanding of these cohesive forces will allow the most efficient methods of anti-clumping to be considered. This understanding will also allow for the best drying method to be chosen based on the cost it takes to dry the material.

Figure 25 - Picture of Ferrous Oxide Mixed with Moisture

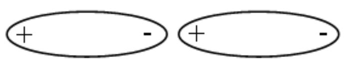

Figure 27 - Diagram Depicting London Dispersion Force Between Two molecules

4.2 Drying NFR in the Metal Recycling Industry

One of the main factors metal recycling companies must consider is the market price of each type of metal product. As in every industry, money is a key driving factor in the metal recycling industry. Some processing is expensive, so certain metal products are only processed when the market price is high. When the price of the product drops too low, processing may have to slow down or stop to accommodate. For example, let us say one product is 95% aluminum. Special processing is required to separate this aluminum from the other nonferrous metals. If the market price of aluminum falls below a desirable amount, then the processing required to make the 95% pure product would cost more than the profit from selling. Therefore, when the market price is low, a mixed product would be more beneficial to produce because more profit exists than for a 95% pure aluminum product. This same idea exists for the separation and drying of NFR. An increase in yield efficiency must be obtained to create a profit over the cost of drying.

4.2.1 The Effect of Moisture on Screening

There is a significant effect of moisture on screening when the size range of particles is less than ¾”. The results section discussed how this effect causes the distribution of material to change. At specific size ranges there exists a moisture content at which screening does not work as effectively. This is important because current industrial recycling processes are dependent upon the screening of NFR to separate the material into different size ranges. These size ranges are then processed separately, often requiring different machinery for each size range. At current moisture content levels, the screening of material is not as effective due to agglomeration that occurs between molecules.

Due to the amount of material a plant can run (80 tons per hour, Schnitzer estimate); this material has to be separated somehow to allow for the machinery to process the material efficiently. With the moisture content for NFR around 25%, the separation does not produce a true distribution. This is because the more moisture contained in the NFR, the more material agglomerates into the larger size ranges. The small particles less than 1-2.4 mm are the main source of this problem during separation and liberation. These particles clump together, stick to larger particles, and agglomerate, hindering the screening effectiveness. Ben Ghiringhelli reported nonferrous liberation is not obtaining yields representative of the known amount of metals in NFR. The efficiency of nonferrous liberation is the yield of metals versus the actual amount of metals in NFR. The research completed in this paper is working towards the goal of increasing this liberation efficiency. The correlations between moisture and agglomeration lowers the screening effectiveness at specific size ranges. The moisture content begins to increase the weight percent of material in each size range at specific amounts of moisture:

a. NFR from 2.4-4.75 mm begins to agglomerate when moisture content reaches about 4-6%.
b. NFR from 4.75-6.3 mm begins to agglomerate when the moisture content reaches 6-8%.
c. NFR from 6.3-9.5 mm begins to agglomerate when the moisture content reaches 10-14%.

d. NFR from 9.5-13.0 mm begins to agglomerate when the moisture content reaches 14-16%.
e. NFR greater than 13.0 mm begins to agglomerate when the moisture content exceeds 16-18%.

However, further research needs to be done to corroborate the effect of moisture on screening in industrial processes. This research will also be able to determine the relationship between the moisture content and the liberation efficiency. This research should run large samples at different moisture contents through the NFR extraction processes at a Schnitzer plant. This would determine the yield efficiency of nonferrous metals based on the moisture content.

While further research must be conducted to correlate moisture content and liberation efficiency, this research shows that moisture has an effect on screening processes. These processes are important in the recycling of metals, and studies should be completed regarding ways to implement improvements in the effectiveness of screening.

4.2.2 Drying and Screening Process Design

During the processing of NFR, the material must be separated into size ranges. However, with the effects of moisture on screening effectiveness, some sort of drying application should be employed to increase this separation. By effectively separating the NFR into size ranges, the extraction processes can be designed for extraction from each specific size range. The effective separation allows for a reduction in overburdening of equipment. In addition, a reduction of the clumping agent occurs if the smaller particles from 0-2.4 mm in size are removed effectively from the larger size ranges. To achieve the removal of these smaller, agglomerating particles, a process design is required. This design should utilize the following results:

a. NFR from 2.4-4.75 mm begins to agglomerate when moisture content reaches about 4-6%.
b. NFR from 4.75-6.3 mm begins to agglomerate when the moisture content reaches 6-8%.
c. NFR from 6.3-9.5 mm begins to agglomerate when the moisture content reaches 10-14%.
d. NFR from 9.5-13.0 mm begins to agglomerate when the moisture content reaches 14-16%.
e. NFR greater than 13.0 mm begins to agglomerate when the moisture content exceeds 16-18%.

From these results the following process or a similar one could be implemented. First, a screening should occur where material 20 mm and under is taken to an initial drying stage. This material should be dried to between 14-18% moisture content. Then this material could be screened effectively at 9.5-13.0 mm. The larger material could be sent to extraction processing and could most likely be processed with minimal effects to yield from moisture content. However, the material below 9.5-13.0 mm should go to a secondary drying process to drop the moisture content to around 10-15%. At this moisture content, screening at approximately 6 mm could occur with minimal agglomeration effects. Then, the material 6-9.5/13.0 mm could be processed at this 10-15% moisture content. The material less than 6 mm would need to be dried one more time to 4-8% moisture content. Once dried to this moisture content, one additional screening step should occur to cutoff the material from 0-4.75mm in size. The NFR in the size range 4.75-6 mm could then be processed. Depending on the amount of metals in the material less than 4.75 mm in size, a company could pursue further drying and processing of the material in this lowest size range. However, this processing would be dependent on the profit available from the metals in this size range.

George Trezek stated that the NFR in the 4.75-9.5 mm size range is around 17 weight percent metals when the material is completely dried. On the scale of around 14.4 tons per hour (Schnitzer estimate) of material in this size range this amount of metal becomes significant. However, at the 0-4.75 mm size range the weight percentage of metals drops to around 3.64%. Analysis of the profit available from these metals should be conducted along with the cost of drying the material in each of these size ranges to determine the cost-benefit ratio for drying to each moisture content.

In conclusion, further testing of separation and drying combinations should occur to determine the actual effects on overall yield efficiency. Once these effects on efficiency are known, a cost-benefit analysis can be conducted to determine the economic feasibility of drying processes compared to the increased nonferrous yield.

4.4 Recommendations

The following recommendations were made to help Schnitzer Steel Industries determine how to improve the yield efficiency during nonferrous liberation of NFR less than 10mm in size.

1. Complete a detailed analysis on the cause of cohesion on a molecular level.
2. Observe the screening of material in industrial processes for NFR at different moisture contents.
3. Compare yield of nonferrous metals while running NFR at different moisture contents to determine the benefits of drying NFR.
4. Determine the best drying method based on the cohesion analysis and cost-benefit analysis.

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Appendices

Appendix A - Critical Literature Review

The purpose of this critical literature review is to overview extraction metallurgy, bring clarity to the reasons why this project has become important, and to bring the reader up to speed on the extraction techniques available for current recycling procedures.

1.1 History of Extraction Metallurgy

Extraction Metallurgy goes back as far as man has known metals existed. The history consists of two periods: the ancient period, when man knew of only a few metals; and the recent, which encompasses the last two and a half centuries (Gilchrist, 1989). In the ancient period, metals of interest had to be easily reduced from their ores and easily accessible. While iron and aluminum are metals most abundant in Earth's crust, people easily found other metals on the ground or in caves. Among the easiest metals to discover and produce were gold, silver, copper, and mercury followed shortly by the production of tin for its properties of strength and fusibility with other metals. While deposits of iron ore were abundant, the methods of producing iron products were limited to certain locations. China was perhaps the most effluent civilization in this regard, as their deposits had high carbon, phosphorous, and silicon contents, making them easy to melt. This allowed a carburizing process to take place. While other locations were producing iron similar to today's wrought iron, China was able to produce a cast iron formed into many different shapes.

In the recent period of extraction metallurgy around the year 1886 (Gilchrist, 1989), the focus came to the mass production of common metals, with the focus being on iron, then aluminum. Magnesium is added to the list of mass produced metals around the 1930's, followed by beryllium, uranium, titanium, niobium, and other metals from their use in World War II. Today, if you have the money to cover the costs, then you can obtain any metal on the Earth relatively purely. However, in increasing amounts, metals in the current century depend on much of their production from recycling plants, rather than mining operations. Metals commonly purchased from recycling facilities are iron, aluminum, copper, stainless steel, and magnesium amongst others. The majority of these plants operate by buying metal containing products, and then processing them. Through processing, a recycling plant will recover metals and sell them to metal processing plants.

1.2 Generic Extraction Techniques

Industrial mining has existed since the recent period of extraction metallurgy; over the years, much of the techniques used to extract metals from the Earth have not changed significantly except to make the processing of larger quantities possible (Gilchrist, 1989). Additionally, the metal recycling business has adapted many of the processes used over the centuries for mining to fit their needs. Recycling facilities use similar processes to those described in section 1.2.

1.2.1 Size Reduction

In mining, the size to which the engineers reduce the particles depends upon the second step in the process, material separation. This step, in turn, depends upon the particle size of the grains of the several minerals in the untreated ore. At first glance, an engineer might see the possibility to crush the ore to a size, which would crush certain minerals to a smaller range than other minerals based on fracture properties. Table 1 below represents the Volume Concentration of ore possible for different reduction factors.

Table 1

n	Volume Concentration $\frac{n^3}{(n+1)^3} * 100$
0.5	1.2
1.0	12.5
2.0	29.6
3.0	42.1
4.0	51.2
5.0	57.9
10.0	75.1
20.0	86.5

As seen in the table to the left, at a quarter of the original size of the block, we can recover roughly 51 % of the ore mineral in a perfect scenario. This means that a quarter of the original block size is essential, but we would like further reduction to improve this number. However, grinding costs money, so we need to compute a financial analysis using the amount of material that we recover to compare the cost of crushing and separating to the amount of money made from selling the final product.

This, however, is a simplified version of reality. Regardless of the way an ore crushes up, an engineer can always calculate a characteristic length to determine screening for various shapes and sizes. Still though, one must consider that the size to which one would like to crush the material down to might not be economically sensible. This could be due to cost or even the fact that below certain size ranges, some materials may turn to wet, gritty dust that behaves like a sludge, which is hard to separate out and difficult to process. Additionally, to predict the behavior of material, it is essential to run tests to simulate the process on a smaller scale before implementing the process on an industrial scale.

1.2.2 Screening

Screening processes take place to separate the material by size range. The fracture characteristics are different for each type of metal compared, thus the separation by size range has the potential to also sort some of the metals (Rosenqvist, 1983). This type of calculation would consider how much force is implemented during crushing. From this information, an engineer could determine the size of particles that will be formed. In addition, for a composite material, each type of metal would be broken into separate sizes based on parameters such as angle of contact, how the composite is bonded, and the mechanical properties of each material. From this information, specific screening sizes can be determined to best separate the material.

Screening utilizes many different methods of separation, but generally involves the sifting of material across a screen with holes. These holes can be of different shapes, but commonly are circles. The diameter of these holes is the screen size. Given a specific period of time, some material will pass through the screen. However, this period of time must be determined to maximize the amount of material that passes through the screen. This is because the amount of material that passes through depends upon the number of times a particle tries to pass through the screen (Gilchrist, 1989). It is because of this, that some screens implement vibration or shaking to cause the particles to repeatedly bounce on the screen.

1.2.3 Sorting

There are many different methods of sorting for extraction metallurgy, but only a few have been adapted for use in metal recycling. The majority of machinery for metal extraction during recycling processes has been redesigned or created specifically for the purpose of extracting metals from shredded materials. The machines considered for the effect of clumping are discussed in the following section.

1.4 Outline of Schnitzer Metal Recycling Process

Schnitzer Steel Industries uses mechanical separation as a means to recycle metals and sell various products to customers (such as ferrous shred and zorba). Schnitzer Northeast (SNE - located in Everett, MA) first shreds the material coming in to be recycled with a rotating hammer mill. From this shred, the material is separated into two categories: ferrous metals and nonferrous raw. Ferrous material is removed using rotating magnetic drums. After this first separation, the ferrous metals are ready to be shipped. However, the nonferrous raw product is a composition of ferritic dirt, some leftover ferrous metals, waste products (such as foam, rubber, etc.), and nonferrous metal particles. This mixture is processed through cyclones to remove some fuzz from the mixture, but overall the composition remains comprised of these parts. This leftover material is called nonferrous raw. This nonferrous raw must undergo processing to separate out the nonferrous metals. SNE plans to do this processing in the new nonferrous recycling building at SNE. The process begins with separation by screening into size categories. For this project, focus will be directed to particles less than 10 mm in size. This is referred to as “ultrafines” product. Once separated by size, the next step is to remove the remaining ferrous material and ferritic dirt. A magnetic separator is used to pull ferrous material out of the mixture. This step is where some entrapment occurs. As the magnetic separator pulls ferrous product out, the cohesion forces cause some nonferrous metals to be lost. This is the first point where yield efficiency is lost due to cohesion forces. The leftover nonferrous raw still has waste product mixed in, so a final step is needed. SNE uses the Steinert Eddy Currents and other sorting machinery to separate the remaining nonferrous metals from the leftover waste products. Cohesion forces also affect these final separation processes. In addition, when ferritic material is left in the mixture, it can cause clumping on the magnets used for these separation processes, which reduces the efficiencies of these magnets. The clumping of material also causes reduction in the separation efficiency of these machines by increasing the forces needed to cause separation to occur.

Appendix B – Moisture Analysis Procedures and Spreadsheets

Moisture Analysis Procedure

1 Purpose

1.1 To determine the amount of moisture contained in the material less than $\frac{3}{8}$" at Schnitzer Northeast.

1.2 To determine the effect of moisture on the density of the material.

1.3 To determine if weather (air temperature, humidity, and general weather) has any correlation with the amount of moisture in the material.

2 Materials

2.1 Plastic baggies

2.2 Scale to .01 g accuracy, limit of 750 grams, 100 gram calibration weight

2.3 Furnace capable of 110 ˚C ± 5˚C for extended periods of time

2.4 Aluminum foil, 2 aluminum trays

2.5 750 mL beaker with 50 mL increments

3 Collecting Samples

3.1 Samples were collected at random times during the day.

3.2 Samples were collected on random days.

3.3 The material was taken before the vibratory feeder after the 3/8" screen using plastic baggies.

3.4 After a sample was taken, it was immediately weighed and the known weight of the plastic bag was subtracted. This weight, along with the humidity, air temperature, and weather were recorded.

3.5 A density calculation was also done for every sample immediately after it was taken.

- 3.5.1 Scale is zeroed with the beaker
- 3.5.2 Material is poured into the beaker and weighed
- 3.5.3 Volume of material is noted in mL
- 3.5.4 Weight is divided by Volume to get g/mL; then converted to lb/ft.^3

4 Drying Procedure

4.1 The furnace was heated to 110˚C

4.2 A bag of the material is placed on a sheet of aluminum foil

4.3 This material + foil is weighed, and the weight recorded.

4.4 This foil is then placed on one of the aluminum pans and the pan inserted into the furnace.

4.5 Steps 4.2-4.4 are repeated for a second sample because 2 samples can be dried at once.

- 4.5.1 The top tier inside the furnace dries more quickly, therefore every half hour the top and bottom aluminum pans would be switched.
- 4.5.2 This can be observed in the % moisture evaporated from the samples every ½ hour; one will decrease dramatically, then the other the next ½ hour

4.5.3 This does make the ½ hour readings pretty insubstantial, however, the 2 hour drying time is verified by the approximately less than 1% moisture drop over the last ½ hour.

4.6 At the end of the 2-hour drying period, the samples are weighed first with the foil.

4.7 Then the material is poured into the 750 mL beaker to get a second density calculation.

4.7.1 Scale is first zeroed with beaker

4.7.2 The volume of material is also recorded

4.7.3 Then the weight/volume calculation and conversion are performed and recorded.

4.8 The sample is then poured back into the plastic bag to be reweighed for comparison to the original weight taken directly after collecting.

4.9 Steps 4.2-4.8 were repeated for all samples.

4.10 One note: Minimal material was lost during transfers. The average difference between experimental and calculated moisture contents is .5%.

4.10.1 The calculated moisture content was calculated by adding the amount of material lost to the final weight and recalculating the moisture % with this value.

4.10.2 These values were then subtracted from the experimental moisture % values; from which an average was determined to be .5%

Moisture Content Spreadsheets

Collection Information

Sample #	Time	Weight Initial	Temp. (˚ F)	Humidity	Weather	Description Of Material	Density Calculation (Pre-drying)	Density Calculation (Post-Drying)
Date:7/6		grams				Small puddles on ground, use of water truck	lb/ft^3	lb/ft^3
1	11:11	185.71	94 F	62%	Sunny	Lots of fuzz, clumpy	n/a	27.46
2	11:51	208.83	95 F	62%	Sunny	Lots of fuzz, clumpy	n/a	31.52
3	12:33	207.77	97 F	61%	Sunny	More dirt, moist And clumpy	n/a	30.86
4	1:11	227.42	98 F	60%	Sunny	Moist and clumpy Lots of dirt	62.43	45.75
5	1:53	223.34	98 F	59%	Sunny	Very moist, clumpy Fuzz	61.22	45.53
Date: 7/7						Small puddles, use of water truck		
6	9:11	250.92	81 F	49%	Sunny	Clumpy, moist, Lots of Dirt	44.6	34.56
7	9:41	219.53	81 F	49%	Sunny	Clumpy, moist dirt	41.96	31.98
8	10:07	197.92	83 F	47%	Sunny	Clumpy, moist dirt	45.44	35.02
9	10:33	168.76	83 F	46%	Sunny	Clumpy, moist, More fuzz	47.7	30.46
10	11:01	180.13	85 F	45%	Sunny	Clumpy, moist, Back to more dirt	44.84	35.75
Date: 7/8						Very dry ground, water truck used		
11	8:47	209.92	74 F	78%	Sunny	Not much material Clumpy, dirt	42.18	29.38
12	9:40	210.41	76 F	76%	Sunny	Lots of bigger pieces Less moisture, clumpy	43.65	30.3
13	10:10	203.87	76 F	76%	Sunny	Less clumpy, more Rocklike pieces	42.33	29.84
14	10:35	204.11	79 F	68%	Sunny	Very clumpy, moist More dirt, less pieces	42.32	25.76
15	11:10	177.79	79 F	68%	Sunny	More metallic pieces, less dirt	36.79	25.03

Date: 7/12						Big water puddles everywhere, using bulldozers to move water		
16	6:30	243.98	72 F	80%	Cloudy	Moderate mix of dirt and particles	52.92	37.89
17	7:15	170.48	73 F	87%	Cloudy	More clumpy, lots of moisture, moderate mix	53.22	38.34
18	8:00	178.44	74 F	88%	Partly Cloudy	Puddles evaporate a little, more particles, clumping	49.45	34.45
19	8:45	246.77	74 F	82%	Fair	Puddles evaporate a little, more particles, clumping	46.89	36.62
20	9:20	188.91	77 F	76%	Sunny	Lots of particles, more fuzz clumping	38.9	28.75
Date: 7/14						Still decent sized puddles; rained the night before		
21	6:15	213.26	76 F	94%	Cloudy	Less dirt, more particles, was first material for day	40.97	34.79
22	6:45	223.45	77 F	89%	Mostly Cloudy	More dirt, more clumping	42.92	36.12
23	7:00	198.76	78 F	84%	Mostly Cloudy	Very clumpy, lots of material	41.36	29.74
24	7:20	230.97	78 F	84%	Mostly Cloudy	More particles, less dirt, still clumpy	41.2	34.63
25	7:51	174.07	78 F	84%	Mostly Cloudy	Very wet & clumpy, more particles, more dirt	43.47	33.63
Date: 7/15						Rained the night before, Lots of mud everywhere		
26	8:45	208.67	66 F	93%	Cloudy	Average mixture, average moisture	43.42	33.15
27	9:15	226.55	67 F	92%	Cloudy	Average mixture, little more moisture	47.15	34.75
28	9:25	206.14	67 F	92%	Cloudy	Average mixture, average moisture	42.9	31.62
29	9:35	162.01	67 F	92%	Cloudy	Average mixture, average moisture	40.46	26.23
30	9:50	252.38	69 F	91%	Cloudy	Big clumps, lots of dirt	45.02	30.94
31	10:00	196.03	70 F	91%	Cloudy	Average mixture + more dirt, a lttle more moisture	40.79	31.41
32	10:15	160.62	70 F	90%	Light Drizzle	Almost no dirt, lots of wood chips and insulated wire	33.43	24.77
33	10:25	157.19	70 F	90%	Light Drizzle	More dirt, moisture, clumping, & more fuzz	32.71	24.01
Date: 7/16						Rained the night before, lots of mud, but dried by 1 p.m.		
34	1:15	186.89	87 F	59%	Fair	Less mosture, more dirt, average clumpy	46.67	
35	2:30	157.06	90 F	54%	Fair	More particles, less dirt not too clumpy	35.66	
36	2:40	201.58	90 F	54%	Fair	More dirt, more particles, little clumpy	41.95	
37	2:50	202.34	90 F	54%	Fair	Very clumpy, lots of dirt	42.11	
38	3:30	145.4	91 F	52%	Partly Cloudy	Very Moist, clumpy	36.31	
39	3:45	221.37	91 F	51%	Partly Cloudy	Extremely Moist, clumpy, lots of dirt	46.07	
40	4:00	261.97	91 F	51%	Partly Cloudy	Extremely Moist, clumpy, lots of dirt	43.61	

Drying Information

Sample	Initial (grams)	Weight before Furnace* (w/foil)	½ hour (w/foil)	% evap after 1/2 hr	1 hour (w/foil)	% evap after 1 hr	1 ½ hours (w/foil)	% evap after 1 1/2 hr	2 hours (w/foil)	% evap after 2 hrs	Final Weight (in baggie)	% Moisture Evaporated
1	185.71	190.87	172.87	9.43%	165.42	13.33%	140.43	26.43%	138.44	27.47%	130.13	29.93%
2	208.83	212.41	185.32	12.75%	158.72	25.28%	145.20	31.64%	145.11	31.68%	138.04	33.90%
3	200.77	207.71	157.42	24.21%	142.30	31.49%	144.63	30.37%	144.61	30.38%	136.30	32.11%
4	227.42	233.22	225.59	3.27%	196.14	15.90%	182.34	21.82%	181.55	22.16%	173.25	23.82%
5	223.34	229.30	210.86	8.04%	202.12	11.85%	180.95	21.09%	180.76	21.17%	172.39	22.81%
6	250.92	259.92	245.77	5.44%	216.37	16.76%	204.17	21.45%	198.54	23.61%	188.30	24.96%
7	219.53	227.97	196.11	13.98%	182.97	19.74%	175.93	22.83%	175.99	22.80%	166.54	24.14%
8	197.92	206.56	203.46	1.50%	153.81	25.54%	150.44	27.17%	150.88	26.96%	140.37	29.08%
9	168.76	178.06	157.93	11.31%	143.98	19.14%	132.33	25.68%	131.79	25.99%	122.04	27.68%
10	180.13	186.74	165.28	11.49%	147.96	20.77%	139.02	25.55%	136.72	26.79%	129.42	28.15%
11	209.92	216.87	176.48	18.62%	166.89	23.05%	161.44	25.56%	161.30	25.62%	153.52	26.87%
12	210.41	216.06	205.36	4.95%	183.56	15.04%	165.47	23.41%	163.39	24.38%	157.75	25.03%
13	203.87	210.12	196.66	6.41%	180.22	14.23%	166.03	20.98%	161.57	23.11%	155.32	23.81%
14	204.11	211.39	190.20	10.02%	162.12	23.31%	159.18	24.70%	150.79	28.67%	144.44	29.23%
15	177.79	183.58	175.52	4.39%	153.76	16.24%	139.76	23.87%	136.72	25.53%	130.30	26.71%
16	254.32	260.44	234.41	9.99%	203.67	21.80%	194.81	25.20%	190.67	26.79%	182.09	28.40%
17	170.48	176.20	149.08	15.39%	134.75	23.52%	130.49	25.94%	130.17	26.12%	122.82	27.96%
18	178.44	184.94	175.24	5.24%	152.06	17.78%	146.85	20.60%	146.19	20.95%	137.96	22.69%
19	248.53	255.15	225.28	11.71%	217.35	14.81%	213.27	16.41%	213.45	16.34%	205.30	17.39%
20	189.91	196.40	181.81	7.43%	162.94	17.04%	159.01	19.04%	157.99	19.56%	149.67	21.19%
21	215.26	222.79	191.00	14.27%	180.13	19.15%	175.28	21.33%	175.25	21.34%	167.18	22.34%
22	231.45	238.01	221.77	6.82%	209.63	11.92%	197.64	16.96%	196.84	17.30%	188.01	18.77%
23	198.76	205.72	180.59	12.22%	159.25	22.59%	151.90	26.16%	150.97	26.61%	142.93	28.09%
24	233.97	241.85	214.19	11.44%	199.63	17.46%	189.07	21.82%	188.75	21.96%	180.29	22.94%
25	177.07	185.83	171.72	7.59%	146.97	20.91%	143.08	23.00%	142.73	23.19%	134.65	23.96%
26	202.02	209.86	202.79	3.37%	178.33	15.02%	171.35	18.35%	167.45	20.21%	159.31	21.14%
27	217.35	224.91	200.41	10.89%	190.45	15.32%	175.06	22.16%	174.58	22.38%	166.97	23.18%
28	197.74	205.72	187.28	8.96%	160.65	21.91%	160.39	22.03%	159.93	22.26%	151.93	23.17%
29	158.87	167.02	148.33	11.19%	137.43	17.72%	123.59	26.00%	123.67	25.95%	115.52	27.29%
30	251.38	260.58	224.17	13.97%	209.28	19.69%	195.13	25.12%	195.09	25.13%	185.83	26.08%
31	196.03	203.36	186.19	8.44%	160.25	21.20%	152.06	25.23%	146.43	27.99%	138.36	29.42%
32	160.62	168.73	150.90	10.57%	128.47	23.86%	118.84	29.57%	117.72	30.23%	109.12	32.06%
33	157.19	163.19	124.13	23.94%	114.44	29.87%	113.09	30.70%	113.18	30.65%	105.75	32.72%
34	186.89	193.37	167.62	13.32%	159.26	17.64%	147.89	23.52%	143.77	25.65%	137.55	26.40%
35	157.06	163.44	158.39	3.09%	140.08	14.29%	128.98	21.08%	124.66	23.73%	118.08	24.82%
36	201.58	208.43	185.66	10.92%	174.82	16.13%	156.39	24.97%	153.12	26.54%	145.92	27.61%
37	202.34	209.78	193.14	7.93%	172.56	17.74%	159.18	24.12%	154.94	26.14%	146.84	27.43%
38	145.4	151.88	137.65	9.37%	128.71	15.26%	120.41	20.72%	118.35	22.08%	111.42	23.37%
39	221.37	228.01	208.73	8.46%	191.22	16.14%	178.95	21.52%	173.77	23.79%	166.71	24.69%
40	261.97	268.23	241.82	9.85%	219.97	17.99%	207.13	22.78%	203.99	23.95%	197.45	24.63%

Summary - *Pre-dry Density Values were not calculated for the first three samples

Sample Number	Date Taken	Time of Day	Humidity	Temperature	Original Weight	Final Weight	Moisture Content	Pre-Dry Density	Post-Dry Density	% Density Change
1	6-Jul	11:11	62%	94 F	185.71	130.13	29.93%	n/a	27.46	#VALUE!
2	6-Jul	11:51	62%	95 F	208.83	138.04	33.90%	n/a	31.52	#VALUE!
3	6-Jul	12:33	61%	97 F	200.77	136.3	32.11%	n/a	30.86	#VALUE!
4	6-Jul	1:11	60%	98 F	227.42	173.25	23.82%	62.43	45.75	26.72%
5	6-Jul	1:53	59%	98 F	223.34	172.39	22.81%	61.22	45.53	25.63%
6	7-Jul	9:11	49%	81 F	250.92	188.3	24.96%	44.6	34.56	22.51%
7	7-Jul	9:41	49%	81 F	219.53	166.54	24.14%	41.96	31.98	23.78%
8	7-Jul	10:07	47%	83 F	197.92	140.37	29.08%	45.44	35.02	22.93%
9	7-Jul	10:33	46%	83 F	168.76	122.04	27.68%	47.7	30.46	36.14%
10	7-Jul	11:01	45%	85 F	180.13	129.42	28.15%	44.84	35.75	20.27%
11	8-Jul	8:47	78%	74 F	209.92	153.52	26.87%	42.18	29.38	30.35%
12	8-Jul	9:40	76%	76 F	210.41	157.75	25.03%	43.65	30.3	30.58%
13	8-Jul	10:10	76%	76 F	203.87	155.32	23.81%	42.33	29.84	29.51%
14	8-Jul	10:35	68%	79 F	204.11	144.44	29.23%	42.32	25.76	39.13%
15	8-Jul	11:10	68%	79 F	177.79	130.3	26.71%	36.79	25.03	31.97%
16	12-Jul	6:30	80%	72 F	254.32	182.09	28.40%	52.92	37.89	28.40%
17	12-Jul	7:15	87%	73 F	170.48	122.82	27.96%	53.22	38.34	27.96%
18	12-Jul	8:00	88%	74 F	178.44	137.96	22.69%	49.45	34.45	30.33%
19	12-Jul	8:45	82%	74 F	248.53	205.3	17.39%	46.89	36.62	21.90%
20	12-Jul	9:20	76%	77 F	186.91	149.67	19.92%	38.9	28.75	26.09%
21	14-Jul	6:15	94%	76 F	213.26	167.18	21.61%	40.97	34.79	15.08%
22	14-Jul	6:45	89%	77 F	223.45	188.01	15.86%	42.92	36.12	15.84%
23	14-Jul	7:00	84%	78 F	198.76	142.93	28.09%	41.36	29.74	28.09%
24	14-Jul	7:20	84%	78 F	230.97	180.29	21.94%	41.2	34.63	15.95%
25	14-Jul	7:51	84%	78 F	174.07	134.65	22.65%	43.47	33.63	22.64%
26	15-Jul	8:45	93%	66 F	202.02	159.31	21.14%	43.42	33.15	23.65%
27	15-Jul	9:15	92%	67 F	217.35	166.97	23.18%	47.15	34.75	26.30%
28	15-Jul	9:25	92%	67 F	206.14	151.93	26.30%	42.9	31.62	26.29%
29	15-Jul	9:35	92%	67 F	162.01	115.52	28.70%	40.46	26.23	35.17%
30	15-Jul	9:50	91%	69 F	252.38	185.83	26.37%	45.02	30.94	31.27%
31	15-Jul	10:00	91%	70 F	196.03	138.36	29.42%	40.79	31.41	23.00%
32	15-Jul	10:15	90%	70 F	160.62	109.12	32.06%	33.43	24.77	25.90%
33	15-Jul	10:25	90%	70 F	157.19	105.75	32.72%	32.71	24.01	26.60%
34	16-Jul	1:15	87 F	87 F	186.89	137.55	26.40%	46.67	31.65	32.18%
35	16-Jul	2:30	90 F	90 F	157.06	118.08	24.82%	35.66	23.41	34.35%
36	16-Jul	2:40	90 F	90 F	201.58	145.92	27.61%	41.95	29.75	29.08%
37	16-Jul	2:50	90 F	90 F	202.34	146.84	27.43%	42.11	27.44	34.84%
38	16-Jul	3:30	91 F	91 F	145.4	111.42	23.37%	36.31	22.31	38.56%
39	16-Jul	3:45	91 F	91 F	221.37	166.71	24.69%	46.07	30.72	33.32%
40	16-Jul	4:00	91 F	91 F	261.97	197.45	24.63%	43.61	28.99	33.52%

Appendix C – Sieve Testing Procedure and Spreadsheets

Accuracy – In general, for sieve analyses, an experiment with unspecified sieve types and unspecified technique, one could expect approximately 8% error (German, 1984). For the experiment described below, all screen types are from the same manufacturer, and all adhere to ASTM standards. According to German this reduces the error to 4%. In addition, for a sieve analysis conducted under perfect conditions, it is not possible to obtain lower than 1% error.

Sieve Testing Procedure

1. Purpose

1.1 Use sieve analysis to determine the particle size distribution for material on the size range < ¾ in. at Schnitzer Northeast. Distribution will be determined for material dried to near 0 % moisture (for a specific time period), 10 %, 20 %, and 30 % moisture.

2. Materials

2.1 11 Standard U.S. sieves and bottom pan with 8 in. diameter, 2 in. depth, meeting requirements of ASTM E11 & AASHTO M92, in the following sizes:

- 19.0 mm (3/4 in)
- 16.0 mm (5/8 in)
- 12.5 mm (1/2 in)
- 9.5 mm (3/8 in)
- 6.7 mm. (265 in)
- 4.75 mm (No. 4)
- 3.35 mm (No. 6)
- 2.0 mm (No. 10)
- 1.0 mm (No. 18)
- .50 mm (No. 35)
- Bottom pan

Numbers in parenthesis are conversion approximations to show U.S. alternate sizes and may not be exact conversions.

2.2 Hand operated sieve shaker with capacity for ten 8 in. sieves plus bottom pan

2.3 Scale to weigh material to .02 lb accuracy

2.4 4 x 5-gallon buckets; Mark each one using tape measure by gallon increments

2.5 Furnace to handle drying of 5 gallons of material at a time

2.6 Spray bottle with large capacity

2.7 1000 mL beaker

3. Collecting Samples, Drying Time, & Sieve Resonance Time

3.1 Sample collection

3.1.1 Take a 5-gallon bucket and fill with 5 gallons of sample from ¾” cut-off

3.1.2 Immediately weigh the sample, subtract bucket weight, and record.

3.1.3 Lay sample in drying pan and dry overnight in furnace at X Degrees C (still t.b.d./depends on capabilities of furnace)

3.1.4 After drying, divide the 5-gallon sample into 5 approximately equal volume samples (1 gallon each)

3.1.5 Place each smaller sample in a separate gallon Tupperware container and number 1-5

3.2 Determining drying time

3.2.1 Dried overnight in a furnace at X Degrees C. Weights are recorded for before and after

3.3 Determine Sieve Resonance Time (SRT)

3.3.1 Interview with Civil Professor Expert on Sieve Analysis

3.3.2 Determined from experience that Sieve Resonance Time should be 15 minutes

4. Sieve Analysis Testing Procedure
(first sample should not be the sample used to determine drying time and SRT)

4.1 Prepare the sieves on the sieve shaker

4.1.1 Weigh each sieve and record initial sieve weight

4.1.2 Place the bottom pan on the mechanical sieve shaker

4.1.3 Place all ten sieves on the bottom pan from the fine mesh (No. 35) on bottom to the coarse mesh (3/4 in) on top

4.1.4 Make sure to clean the sieves after each time step 4.2 is completed

4.2 Prepare a 5-gallon sample by drying/separated into 1-gallon batches and it is ready for sieve analysis

4.2.1 Set a timer for SRT minutes

4.2.2 Pour sample 1 into top sieve

4.2.3 Begin rotating the crank on the sieve shaker to perform mechanized shaking (make sure to rotate at as constant rate as possible)

4.2.4 After SRT minutes stop, weigh the material in each sieve and record

4.2.5 Repeat step 4.2 for samples 1-5

4.3 After sieve analysis is complete for dry sample, combine all 5 in 5-gallon bucket and reweigh the whole sample (to calculate material lost during sieving)

4.4 Using weight from 4.3, calculate a 10 % weight addition so that water can be added to simulate 10 percent moisture

4.4.1 For example: If the sample was 20 lbs dry, then 10 % moisture content would be approximately 2.22 lbs, making the total sample weight 22.22 lbs (22.22*.1=2.22)

4.4.2 Weigh out the correct weight of water for 10 % moisture, pour into spray bottle

4.4.3 Use spray bottle to evenly spray moisture into material while spread out in a pan

4.5 Once again, separate the 5-gallon sample into 5 approximately even by volume (1 gallon) samples

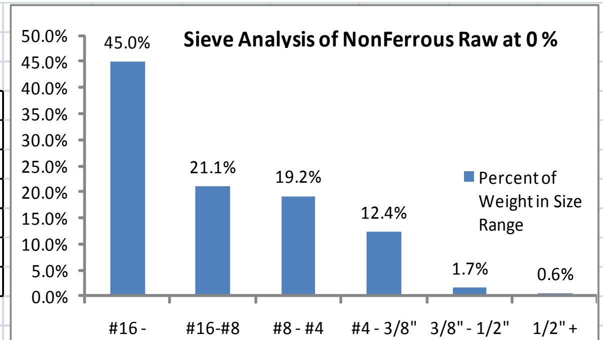
4.6 Conduct 4.2-4.5 for 0, 10, 20, and 30 % moisture contents

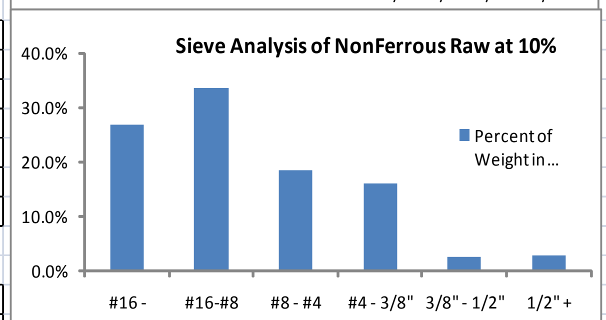
Repeat 4.2-4.6 for 5-gallon samples 1-4

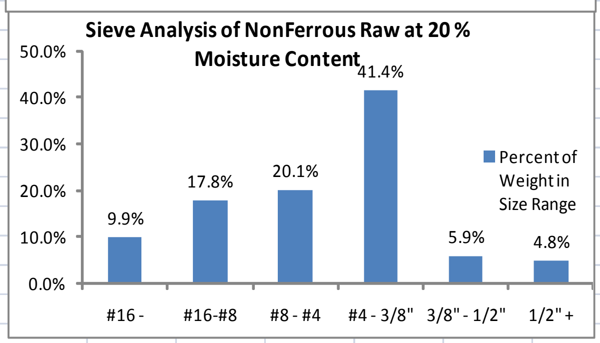
Sieve Data Sheets

Initial Sieve Test Data

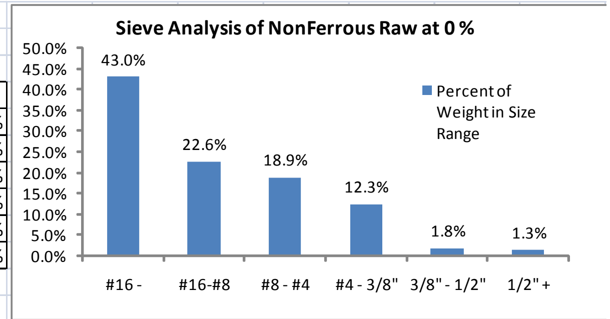
	Sample 1			
	From 3/8" Screen			
		0%		
Total Weight of Material		Size Range	Weight in lbs	Percent Weight
24.636	0% Moisture	#16 -	11.078	45.0%
24.632	After Sieving	#16-#8	5.196	21.1%
0.004		#8 - #4	4.74	19.2%
		#4 - 3/8"	3.058	12.4%
		3/8" - 1/2"	0.416	1.7%
		1/2" +	0.144	0.6%
			24.632	
		10%		
27.373	10% Moisture	Size Range	Weight in lbs	Percent Weight
27.048	After Sieving	#16 -	7.218	26.7%
0.325		#16-#8	9.066	33.5%
		#8 - #4	4.956	18.3%
		#4 - 3/8"	4.368	16.1%
		3/8" - 1/2"	0.66	2.4%
		1/2" +	0.78	2.9%
			27.048	
		20%		
30.795	20% Moisture	Size Range	Weight in lbs	Percent Weight
30.11	After Sieving	#16 -	2.978	9.9%
0.685		#16-#8	5.372	17.8%
		#8 - #4	6.056	20.1%
		#4 - 3/8"	12.48	41.4%
0.685	Total Weight Lost	3/8" - 1/2"	1.764	5.9%
2.22%	% Lost	1/2" +	1.46	4.8%
2.22%	% Error		30.11	

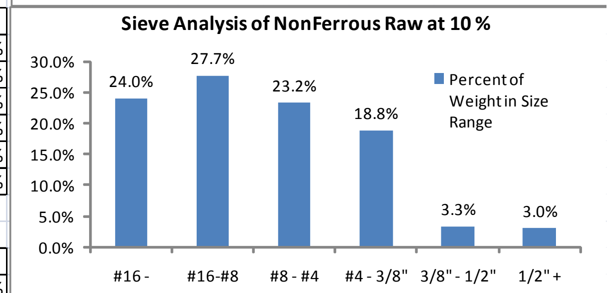


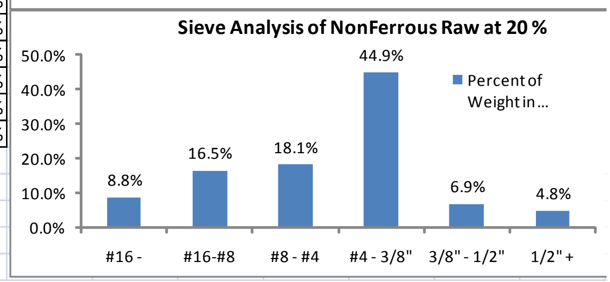




	Sample 2			
	From 3/8" Screen			
		0%		
Total Weight of Material		Size Range	Weight in lbs	Percent Weight
28.429	0% Moisture	#16 -	12.158	43.0%
28.277	After Sieving	#16-#8	6.403	22.6%
0.152		#8 - #4	5.343	18.9%
		#4 - 3/8"	3.491	12.3%
		3/8" - 1/2"	0.522	1.8%
		1/2" +	0.36	1.3%
			28.277	
		10%		
31.588	10% Moisture	Size Range	Weight in lbs	Percent Weight
30.993	After Sieving	#16 -	7.433	24.0%
0.595		#16-#8	8.571	27.7%
		#8 - #4	7.203	23.2%
		#4 - 3/8"	5.834	18.8%
		3/8" - 1/2"	1.022	3.3%
		1/2" +	0.93	3.0%
			30.993	
		20%		
35.536	20% Moisture	Size Range	Weight in lbs	Percent Weight
34.855	After Sieving	#16 -	3.054	8.8%
0.681		#16-#8	5.761	16.5%
		#8 - #4	6.319	18.1%
		#4 - 3/8"	15.647	44.9%
0.681	Total Weight Lost	3/8" - 1/2"	2.399	6.9%
1.92%	% Lost	1/2" +	1.675	4.8%
1.92%	% Error		34.855	



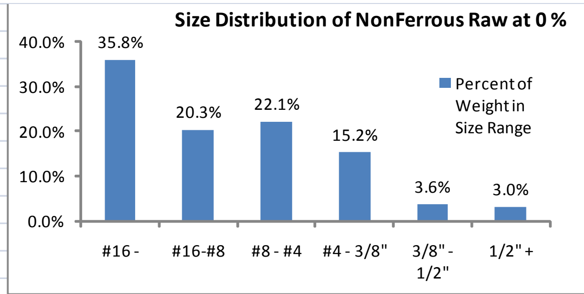




Sample 3
From 3/4" Screen

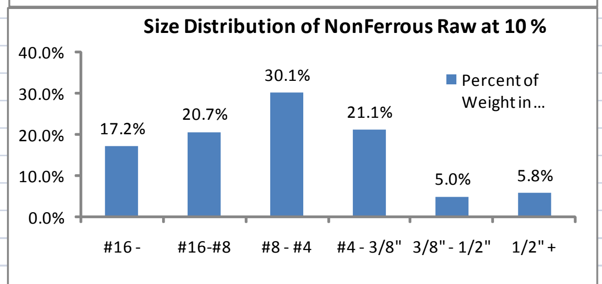
0%

Total Weight of Material		Size Range	Weight in lbs	Percent Weight
21.819	0% Moisture	#16 -	7.622	35.8%
21.262	After Sieving	#16-#8	4.308	20.3%
		#8 - #4	4.702	22.1%
		#4 - 3/8"	3.234	15.2%
		3/8" - 1/2"	0.756	3.6%
		1/2" +	0.64	3.0%
			21.262	



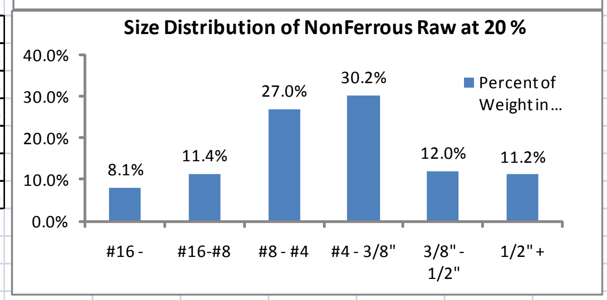
10%

Total Weight of Material		Size Range	Weight in lbs	Percent Weight
24.243	10% Moisture	#16 -	4.128	17.2%
23.975	After Sieving	#16-#8	4.960	20.7%
		#8 - #4	7.224	30.1%
		#4 - 3/8"	5.065	21.1%
		3/8" - 1/2"	1.198	5.0%
		1/2" +	1.400	5.8%
			23.975	

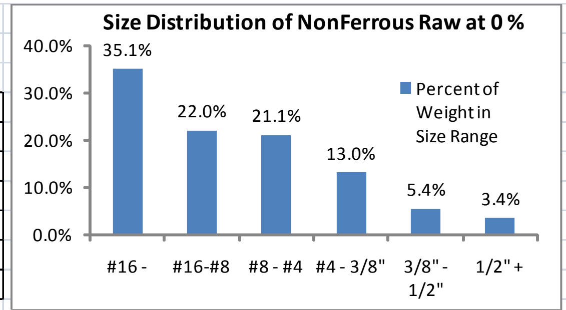


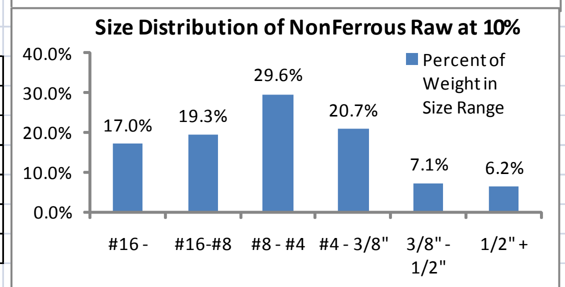
20%

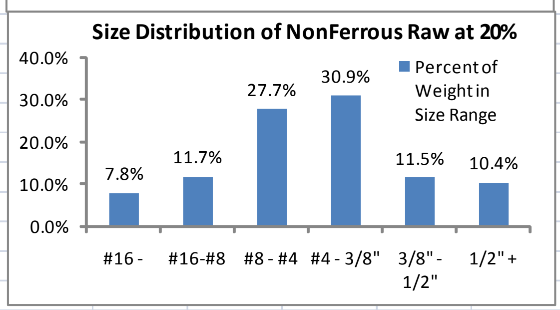
Total Weight of Material		Size Range	Weight in lbs	Percent Weight
27.274	20% Moisture	#16 -	2.347	8.1%
27.047	After Sieving	#16-#8	3.325	11.4%
		#8 - #4	7.851	27.0%
		#4 - 3/8"	8.785	30.2%
		3/8" - 1/2"	3.495	12.0%
		1/2" +	3.244	11.2%
			29.047	



	Sample 4			
	From 3/4" Screen			
		0%		
Total Weight of Material		Size Range	Weight in lbs	Percent Weight
27.514	0% Moisture	#16 -	9.602	35.1%
27.392	After Sieving	#16-#8	6.026	22.0%
0.122		#8 - #4	5.782	21.1%
		#4 - 3/8"	3.566	13.0%
		3/8" - 1/2"	1.491	5.4%
		1/2" +	0.925	3.4%
			27.392	
		10%		
Total Weight of Material		Size Range	Weight in lbs	Percent Weight
30.571	10% Moisture	#16 -	5.113	17.0%
30.093	After Sieving	#16-#8	5.822	19.3%
0.478		#8 - #4	8.915	29.6%
		#4 - 3/8"	6.241	20.7%
		3/8" - 1/2"	2.129	7.1%
		1/2" +	1.873	6.2%
			30.093	
		20%		
Total Weight of Material		Size Range	Weight in lbs	Percent Weight
34.393	20% Moisture	#16 -	2.686	7.8%
34.227	After Sieving	#16-#8	4.021	11.7%
0.166		#8 - #4	9.471	27.7%
		#4 - 3/8"	10.570	30.9%
		3/8" - 1/2"	3.927	11.5%
		1/2" +	3.552	10.4%
			34.227	







Final Sieve Tests

⅜” sample with 2% moisture content increments

Sieve Number	Size Range (mm)	0%	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%
<#16	< 1 mm	1.941	1.812	1.602	1.341	0.953	0.905	0.826	0.752	0.661	0.551	0.503
#16-#8	1 - 2.4	0.924	1.157	1.229	1.498	1.299	1.256	1.178	1.149	1.138	0.947	0.912
#8 - #4	2.4 - 4.75	0.870	0.998	1.136	1.171	1.461	1.581	1.494	1.561	1.404	1.261	1.148
#4 - 1/4"	4.75-6.3	0.572	0.549	0.474	0.619	0.797	0.990	0.882	0.832	0.846	0.952	0.995
1/4" - 3/8"	6.3-9.5	0.331	0.354	0.318	0.422	0.417	0.403	0.531	0.682	0.729	0.871	0.925
>3/8"	> 9.5	0.194	0.142	0.162	0.158	0.19	0.205	0.190	0.136	0.185	0.239	0.317
	Totals:	4.832	5.012	4.921	5.209	5.117	5.340	5.101	5.112	4.963	4.821	4.8

	Size Range (mm)	0%	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%
<#16	< 1 mm	40.2%	36.2%	32.6%	25.7%	18.0%	18.1%	16.13%	14.6%	13.2%	11.1%	10.1%
#16-#8	1 - 2.4	19.1%	23.1%	25.0%	28.8%	24.6%	25.1%	23.00%	22.3%	22.7%	19.1%	18.2%
#8 - #4	2.4 - 4.75	18.0%	19.9%	23.1%	22.5%	27.7%	31.6%	29.17%	30.2%	28.0%	25.4%	23.0%
#4 - 1/4"	4.75-6.3	11.8%	11.0%	9.6%	11.9%	15.1%	19.8%	17.22%	16.1%	16.9%	19.2%	19.9%
1/4" - 3/8"	6.3-9.5	6.9%	7.1%	6.5%	8.1%	7.9%	8.0%	10.37%	13.2%	14.5%	17.6%	18.5%
>3/8"	> 9.5	4.0%	2.8%	3.3%	3.0%	3.6%	4.1%	3.71%	2.6%	3.7%	4.8%	6.3%

¾” sample with 2% moisture content increments

Sieve Number	Size Range (mm)	0%	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%
<#16	< 1 mm	1.631	1.512	1.319	1.097	0.893	0.741	0.726	0.685	0.604	0.509	0.438
#16-#8	1 - 2.4	1.082	1.070	1.103	1.104	0.910	0.877	0.842	0.811	0.763	0.738	0.712
#8 - #4	2.4 - 4.75	0.850	0.880	1.001	0.991	1.124	1.112	0.923	0.886	0.814	0.761	0.715
#4 - 1/4"	4.75-6.3	0.572	0.641	0.651	0.843	1.066	1.146	1.137	0.985	0.952	0.934	0.859
1/4" - 3/8"	6.3-9.5	0.349	0.354	0.378	0.392	0.417	0.494	0.671	0.862	0.834	0.841	0.835
3/8" - 1/2"	9.5-13.0	0.324	0.342	0.338	0.339	0.344	0.361	0.389	0.426	0.635	0.709	0.810
1/2" - 5/8"	13.0-16.0	0.192	0.201	0.210	0.234	0.246	0.269	0.312	0.345	0.398	0.508	0.631
	Totals:	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000

	Size Range (mm)	0%	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%
<#16	< 1.0	32.6%	30.2%	26.4%	21.9%	17.9%	14.8%	14.5%	13.7%	12.1%	10.2%	8.8%
#16-#8	1.0 - 2.4	21.6%	21.4%	22.1%	22.1%	18.2%	17.5%	16.8%	16.2%	15.3%	14.8%	14.2%
#8 - #4	2.4 - 4.75	17.0%	17.6%	20.0%	19.8%	22.5%	22.2%	18.5%	17.7%	16.3%	15.2%	14.3%
#4 - 1/4"	4.75-6.3	11.4%	12.8%	13.0%	16.9%	21.3%	22.9%	22.7%	19.7%	19.0%	18.7%	17.2%
1/4" - 3/8"	6.3-9.5	7.0%	7.1%	7.6%	7.8%	8.3%	9.9%	13.4%	17.2%	16.7%	16.8%	16.7%
3/8" - 1/2"	9.5-13.0	6.5%	6.8%	6.8%	6.8%	6.9%	7.2%	7.8%	8.5%	12.7%	14.2%	16.2%
>1/2"	>13.0	3.8%	4.0%	4.2%	4.7%	4.9%	5.4%	6.2%	6.9%	8.0%	10.2%	12.6%